EMPIRICAL RELATIONSHIPS BETWEEN CONSOLIDATION PRESSURE, POROSITY AND PERMEABILITY FOR MARINE SEDIMENTS

A Thesis

by

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CHAPTER I

INTRODUCTION

In an overpressured zone in the earth the pore presure is greater than hydrostatic pressure. Data from over 4,000 wells in the Gulf Coast area shows that pore pressures in oil wells are usually between hydrostatic and overburden or geostatic pressures, but in the overpressured region of the Gulf Coast area, some measured pore water pressures even exceed geostatic pressure and are thought to be the major cause of blowouts and stuck drill stems (18)*.

Since entrapped pore water pressure to a large extent determines the shear strength of the submarine sediments, overpressured sediments are unstable and subject to slide. In the last 20 years, there have also been 19 mobile offshore drilling rig foundation failures that may have involved overpressured marine sediments. During this same time there have been 33 blowouts involving mobile offshore drilling rigs. These failures were distributed all over the world but primarily in areas where the rate of deposition

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The style and format of this thesis follows the <u>Journal of the Geotechnical Engineering Division</u>, Proceedings of the American Society of Civil Engineers.

*The numbers in parentheses refer to citations in the Reference.

is high (29). In the same period there have been 53 blowout accidents involving permanent structures in federal oil and operations in the outer continential shelf of the Gulf of Mexico alone (20). If the hazards of overpressured sediments are to be avoided, better techniques must be developed to locate them. These new techniques will depend on the knowledge of how these zones can develop.

Overpressured sediments have been the subject of much speculation and several theories have been advanced to explain them. It is usually tacitly assumed that given enough time all pore pressures must decrease to a steady state hydrostatic condition, therefore most explainations involve some method of generation of either pressure or additional water.

One group of papers describes the possibility of sediment settling with no decrease in porosity or no expulsion of water (1, 5, 15). Since the water will be heated because of the earth's thermal gradient, pressure will be developed. This process requires an impermeable barrier and some hiatus in the consolidation process.

Another group of papers describes the generation of water by chemical alteration of the minerals (4, 7, 10, 17) According to Powley (18), the cores from many overpressured oil wells are nearly identical mineralogically to the sediments being deposited. It raises doubts as to the reliability of the diagenesis theory. Diagenesis certainly can not explain near surface overpressured sediments.

The mechanical process of sedimentation has generally been overlooked as a source of overpressures, and in fact, it has been thought that it is impossible for pore pressures were to exceed the geostatic pressure. The reason for this belief in Terzaghi's effective stress principal which states the total stress is equal to the sum of the effective stress in the soil and the pore pressure in the water. It is reasoned that the maximum pore pressure would be equal to the maximum total stress or the geostatic stress when the effective stress is zero. This of course is not true; since the area of the mineral and the area of the water is also involved.

Because of deposition the total stress on the underling sediment increases, and tends to change the porosity and the permeability. If in this process the permeability decreases faster than the porosity the water will be entrapped. Further loding will only cause the pressure to increase and not expelled.

The purpose of this study was to develop test equipment and procedures to determine empirically for fine grained marine sediments the relationships between: 1. the consolidation pressure and porosity, and 2. the permeability and porosity. So that the effects of the mechanical process could be reevaluated to determine if progressive burial of sediment automatically causes overpressures to develop.

CHAPTER II

LITERATURE REVIEW

For the marine deposits of the northern Gulf of Mexico Basin, Jones (9) concluded that the decrease in porosity of the fine-grained sediments is rapid during the early burial stages, because the clay has no appreciable load-bearing strength until its porosity has been reduced during compaction to about 45%. If this is true, it may be that grain-to-grain contact in clay becomes an important factor only after the porosity has decreased below 45%. Accordingly, the formation water, during early burial, may flow rapidly into the adjacent sand beds that offer escape.

According to Powley (18), a "seal" over an overpressured zone will have the following properties:

- low permeability ($k \approx 0$),
- completely enclose water or water filled rocks,
- be open at the bottom if the rocks are petroleum filled.

There are two cases of "seals" which are illustrated in Fig. 1 . In Fig. 1A, the seal is completely supported by soil grains and no excess pore water pressure is developed in the soil-water system. The relationship between pore water pressure and depth in discontinuous at the seal and starts at zero again, parallel to the hydrostatic line. In Fig. 1B, the soil grains support very little load of the seal. Most of the load of seal is supported by the pore water which develops excess pressure as a result of the seal load. The pore water pressure below the seal increases abruptly by the amount of overburden pressure.

Also some generalized relations between depth and various properties for overpressured zones as presented by Powley (18) are shown in Fig. 2.

Clay beds drain very slowly because of both their low permeability and their great capacity of adsorb and retain water, even under large compaction pressure. The bulk density of shales varies inversely with the porosity and increases directly with the burial depth in deposits that have normal fluid pressure (9). Weaver and Beck (23) stated that the release of interlayer water may be necessary but not the controlling factor in the development of high pressures in the Gulf of Mexico. Loss of permeability appears to be more critical. However, the rate of sedimentation also plays an important role in the development of overpressured zones.

Hottman (8) has said conventional permeability determinations and calculations of rate of fluid movement through the confining clays in overpressured zones can not explain the long time lag in the rate of fluid loss by material with high fluid pressures. Shales which do not release their fluids as rapidly as the overburden weight is increased can not be explained by calculated permeability characteristics. However, these statements are debatable.

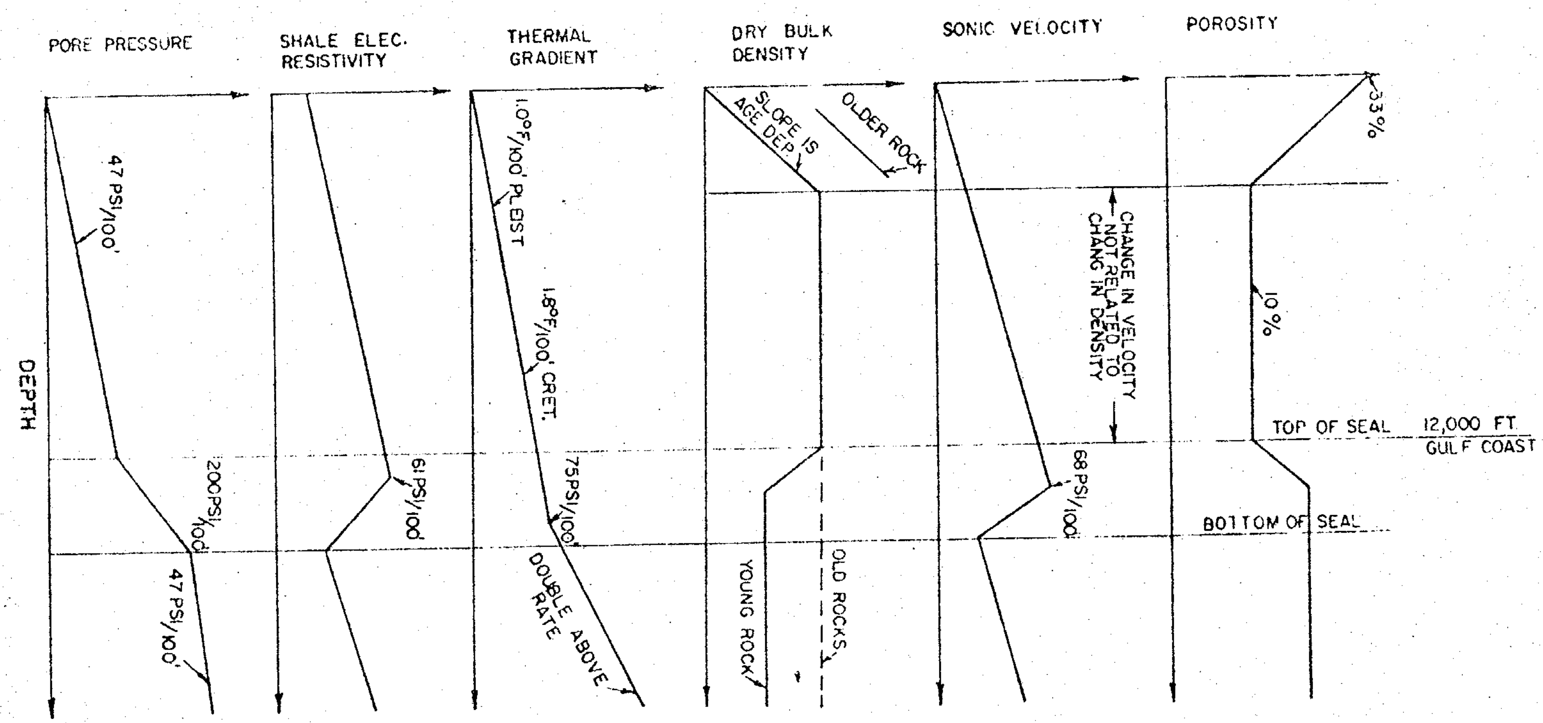


FIG. 2

GENERALIZED RELATIONS BETWEEN DEPTH AND
VARIOUS PROPERTIES FOR OVER PRESSURED REGIONS

"AS PRESENTED BY DAVE POWLEY" MAY 15, 1975

The direct measurement of flow through a soil sample is the best way to determine the permeability of the soil if the pressure gradient and sample size are known.

There have been several equations developed for the calculation of permeability in the past 65 years. Primarily these equations are based on experimentation and experience. In 1911 Hazen (6) proposed experimentally that the permeability of filter sands may be correlated with the effective diameter D_{10}, and he gave the following empirical formula:

$$k = CD_{10}^{2}$$

in which D_{10} is the effective diameter in centimeters and C is a coefficient whose value lies between 100 and 150. The permeability, k, is in centimeters per second.

An equation reflecting the influences of the permeant and the soil characteristics on permeability was developed by Taylor using Poiseuille's law in 1948. This equation is based on considering flow through a porous media similar to the flow through a bundle of capillary tubes. The equation developed was:

$$k = d_s^2 \frac{\gamma}{\mu} \frac{e^3}{(1+e)} C$$

in which k = the Darcy coefficient of permeability

d_s = some effective particle diameter

γ = unit weight of permeant

μ = viscosity of permeant

e = void ratio

C = shape factor

Another equation was proposed by Kozeny and improved by Carman in 1938:

$$k = \left[\frac{g}{k_o S^2}\right] \frac{n^3}{(1-n)^2}$$

in which k_o = factor depending on pore shape and ratio of length of actual flow path to soil bed thickness

S = specific surface area

n = porosity

g = 980 cm/sec^2

For cohesionless soils such as sand, the relationship between permeability and void ratio is reasonably well represented by the Kozeny-Carman equation (27). However, for fine-grained soils as clay, this equation is less successful. This was shown by an important series of experiments by Zunker (13), who investigated the permeabilities of a certain heavy clay soil over a range of porosity from 59.1% to 44.3%. The Zunker's data are given in Table 1. It can be seen that the ratio of permeability k to the porosity function $n^3/(1-n)^2$ is not constant. According to Kozeny's theory, the ratio, which is the term within the brackets, should be a constant. Instead, k decreases much faster than the porosity function. Similar observations were made by Macey (14), so that this general behavior, seems to be common to all clays. Terzaghi (21), Macey (14), and Winterkorn (25) have suggested the existence of an immobile water layer immediately adjacent to the clay particle may explain this behavior.

TABLE 1.-Zunker's Data on Permeabilities of a Clay Soil

Permeability, $k \times 10^{10}$ (cm/sec)	Porosity, n (%)	$k \times 10^{10} \times (1-n)^2/n^3$
9.72	59.1	7.87
8.94	58.7	7.47
9.66	58.2	8.52
7.42	56.2	7.98
2.89	50.3	5.62
2.10	47.9	5.20
1.65	46.0	4.94
1.23	44.3	4.38

Bryant (3) has used statistical analysis of the natural log of permeability versus porosity to develop a permeability prediction equation for different groups of sediments taken from the Gulf of Mexico. Table 2 shows the results of this analysis.

In Table 2 , n is the porosity (in decimals) and k is the coefficient of permeability in centimeters per second. The permeability in Bryant's equation was calculated

TABLE 2.-Bryant's Equations for Permeability-Porosity Relationship

Sediment Group	Equation*	Sediment Type
1	$k = (e)^{n(15.05)-27.37}$	80% clay
2	$k = (e)^{n(14.18)-26.50}$	60-80% clay
3	$k = (e)^{n(15.59)-26.65}$	silty clays and clayey silts
4	$k = (e)^{n(17.51)-26.93}$	sandy clays and silts
all data	$k = (e)^{n(14.30)-26.30}$	

*e is 2.71828

by Terzaghi's consolidation theory. The Terzaghi's formula is stated as follows:

$$k = \frac{C_v a_v \gamma_w}{1+e}$$

in which: 1. k is the coefficient of permeability in cm/sec,

2. C_v is the coefficient of consolidation, where

$$C_v = \frac{0.197H^2}{t_{50}}$$ in log fitting method, or

$$C_v = \frac{0.848H^2}{t_{90}}$$ in square root fitting method.

3. H is the average thickness per drainage surface.

4. t_{50} or t_{90} is the time required for 50% or 90%

completion of primary consolidation,

5. a_v is the coefficient of compressibility,

where $a_v = \frac{0.435C_c}{P}$

6. C_c is the compression index which is the slope of the e-log p curve plotted for many loading increments,

$$C_c = - \frac{de}{d(\log_{10}P)}$$

7. P is the average loading pressure during a single test,

8. e is the average void ratio during the single test, and

9. γ_w is the unit weight of pore fluid

Rubey and Hubbert (19) have concluded that there seems to be an exponential increase in the permeability of a rock corresponding to an increase in porosity. Their conclusion coincides with Bryant's equations for the relationship between permeability and porosity.

Kharaka and Smalley (11) have conducted experiments to determine the permeability for a clay under a compaction pressure of 10,000 psi (68.95 Mpa). The experiment showed the permeability decreasing with increasing compaction pressures, but increasing with increasing hydralic pressure gradients and temperatures. The increase in the conductivity with temperature is equal to that expected from the decrease in the kinematic viscosity of water. The clay samples were compacted with 7,000 psi (48.265 Mpa) and 10,000 (68.95 Mpa) to a thickness of approximately 1.50 to 0.25 cm. The permeabilities of the clays tested were in the range of 2.1×10^{-13} cm/sec to 9.0×10^{-13} cm/sec. The purpose of this test was to determine the ability of soils, clays, and shales (the geologic membranes) to serve as semipermeable membranes. However, they were more interested in the ratio of input solute concentration more than the relationship between permeability and porosity.

CHAPTER III

TEST EQUIPMENT AND PROCEDURES

To simulate the progressive burial of marine sediment two high-powered pressure sources had to be used to develop the necessary high consolidation pressure and high fluid pressure needed to force water through the soil. The pressure had to be easily applied and kept constant for each increment of load.

A hydraulically operated device was first considered for this purpose. The consolidation pressure was to be applied on a floating piston in a closed cell. However, the pressures had to be maintained constant by a high-capacity regulator and accumulator. Also, a series of pressure gauges had to be used to obtain a more accurate reading of the pressure from the low range to the high range. Even though the device was small and easy to operate, the whole system became very expensive and the idea was abandoned.

A dead weight lever system was then considered as the pressure source for consolidation and the permeability tests. The lever system mechanism is simple and accurate. It does not need pressure gauge. The pressure on the soil sample can be calculated directly from the dead weight on the hanger. The pressure can be kept constant for any load without regulator or accumulator. There are no screws, electronics or other devices to be calibrated. All measurements are made in fluids at atmospheric pressure and room temperature.

A. Test Apparatus:

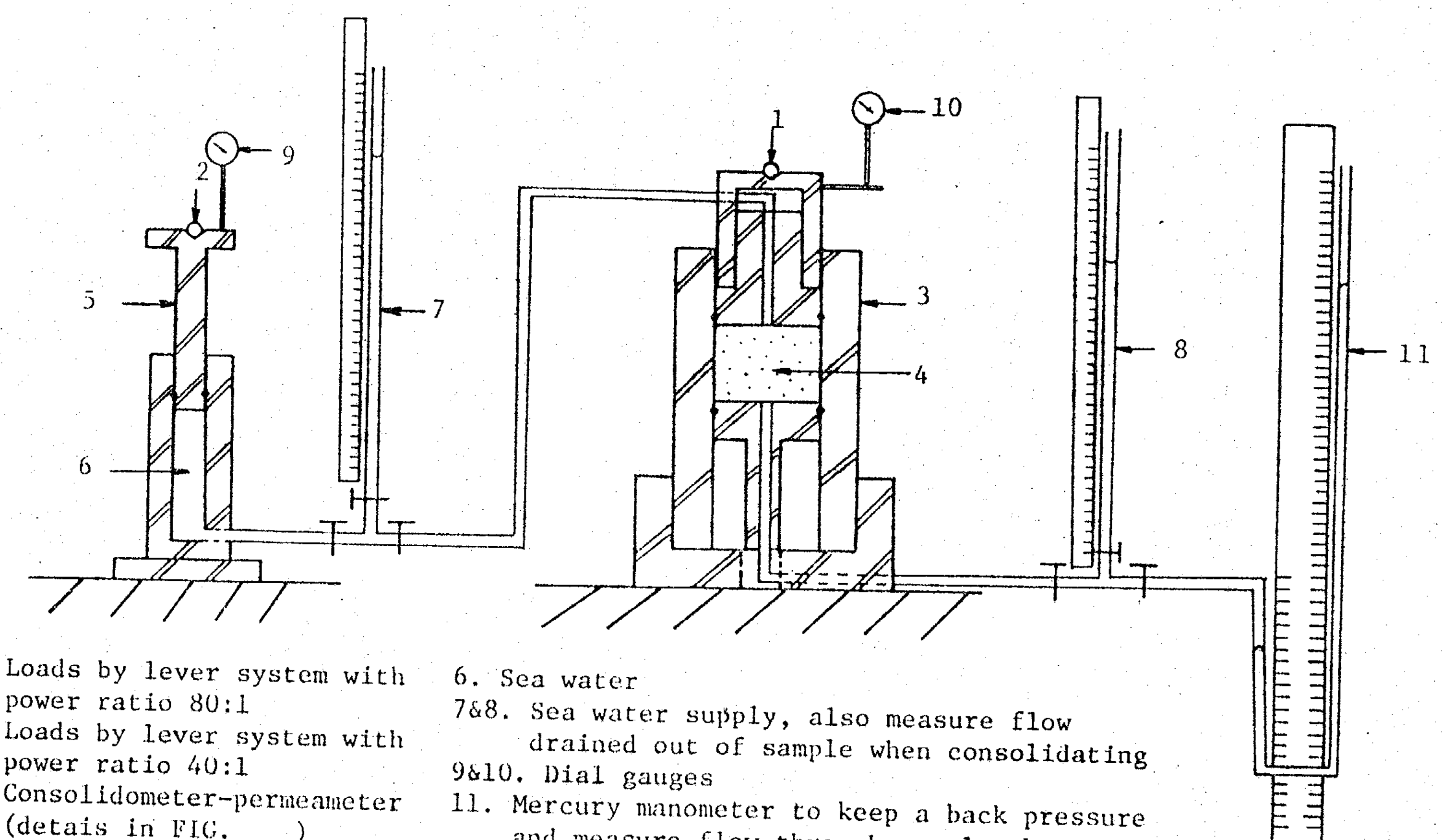
The test apparatus consists of two lever systems, a consolidometer-permeameter, the connecting lines, and a mercury manometer. This equipment is shown schematically in Fig. 3.

1. Lever System:

The lever system for the consolidation test was adapted from the one used by L. A. Wolfskill (26). It consists of two heavy duty lever beams with a combination lever arm ratio of 80:1. Both beams have a counterbalance weight to compensate the weight of the lever beam itself. When there is no weight on the hanger, the beams are at a free and balanced condition. This assures the loads on the hanger are transferred to the soil sample without any correction. Two pictures of these lever systems are in Figs. 4 and 5.

2. Consolidometer-Permeameter

The consolidometer was designed and fabricated to withstand internal pressures up to 10,000 psi (68.95 Mpa) with a safety factor of 2.5. The details of the consolidometer are shown in Fig 6. It contains the soil sample of 2.5 inches (6.35 cm) in diameter and the height of the sample could vary from 2.5 inches (6.35 cm) to less



1. Loads by lever system with power ratio 80:1
2. Loads by lever system with power ratio 40:1
3. Consolidometer-permeameter (detais in FIG.   )
4. Soil sample
5. Piston to apply water pressure
6. Sea water

7&8. Sea water supply, also measure flow drained out of sample when consolidating

9&10. Dial gauges

11. Mercury manometer to keep a back pressure and measure flow through sample when testing permeability

FIG. 3.-Schematic Drawing of Testing Apparatus for High Pressured Consolidation Test and Direct Measurement of Permeability

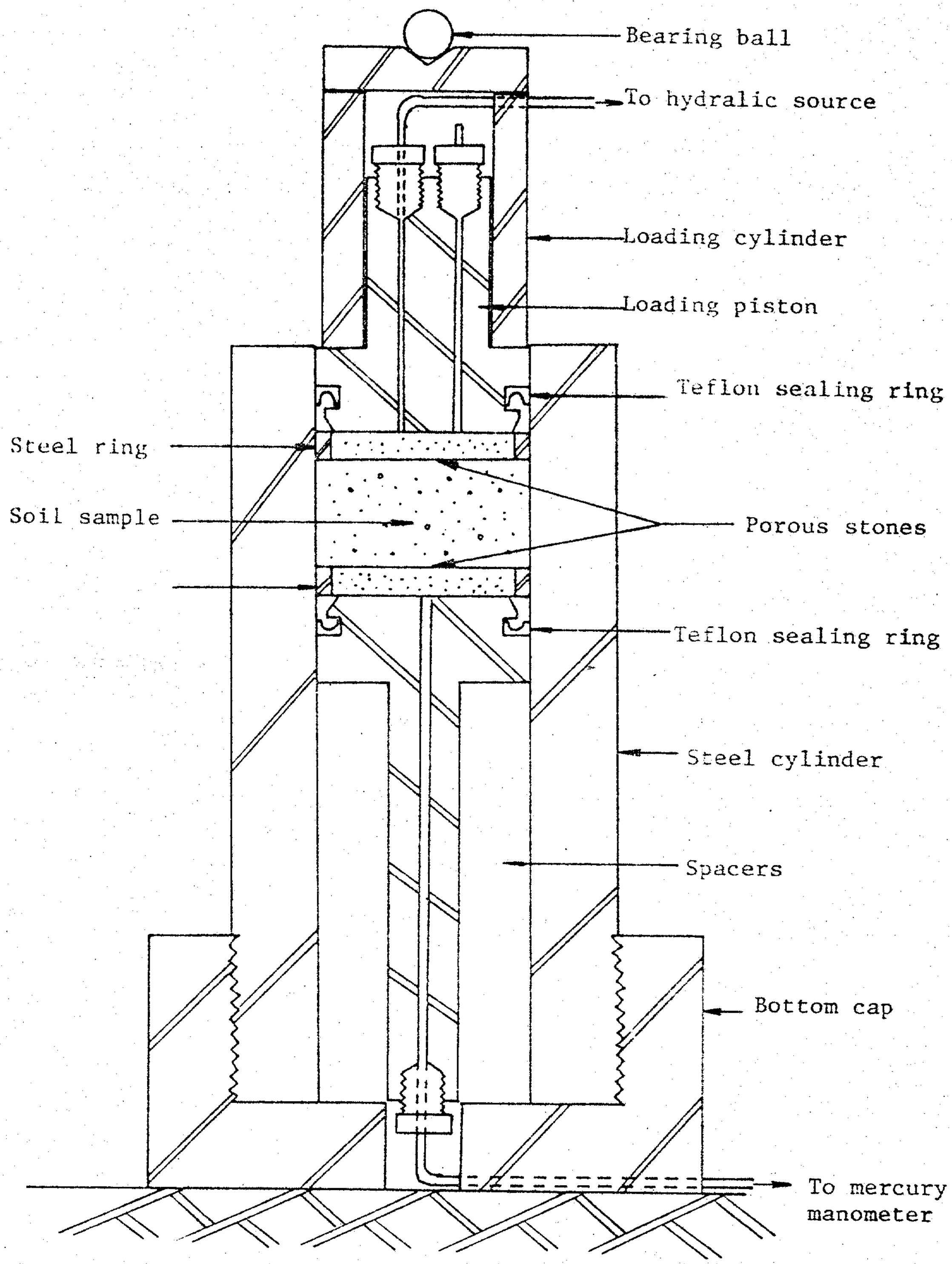


FIG. 6 .-Schematic Drawing of the Consolidometer-Permeameter

than 1/3 inch (0.85 cm). The soil sample is supported between two pistons. As the soil is consolidated the top piston moves and bottom piston is fixed. The surfaces of top and bottom pistons are grooved with shallow trenches so they can collect the expelled water that is drained to the center hole in the pistons. The porous stones between the soil sample and the pistons are 2 inches x 1/4 inch (5.08 cm x 0.635 cm). They are confined with steel rings to give greater strength, and to reduce the friction between porous stone and container surface. The sealing rings on both pistons were U-shaped teflon seal rings. The rings were reinforced with stainless steel springs to withhold pressures up to 10,000 psi (68.95 Mpa). These seals, model number RP-330-2, were manufactured by Fluorocarbon Company of Los Anamitos, California. They show several advantages:

1. High pressure (up to 10,000 psi or 68.95 Mpa)
2. Wide temperature range (-320 F to +500 F)
3. Low friction
4. They can be exposed to any liquid or gas

All the metal part were treated to protect the metal from corrosion by sea water. The coating job was done by process IMFC01660 of the Industrial Metal Finishing Company, Houston, Texas.

A picture of the consolidometer in operation is shown in Fig. 7.

3. Water Pressure Source for the Permeability Test

The hydralic pressure for the permeability test was applied by another loading piston and a cylinder. The piston is operated by a lever system with a power of 40:1. Sea water in the cylinder was compressed by the piston and forced through the soil sample. The schematic details of this device is shown in Fig. 8 . The cylinder has a wall thickness of 1 inch (2.54 cm) and is able to withstand 10,000 psi(68.95 Mpa) with safety of 2.5. The sealing ring on the piston is also a U-shaped teflon seal ring. A picture of the permeameter in operation is shown in Fig. 9.

4. Connecting Lines

All tubings, fittings, and valves connecting the consolidometer-permeameter to the water pressure source were designed to take high pressure. Those between consolidometer and mercury manometer were not. The High Pressure Equipment Company of Erie, Pennsylvania's products were used for this purpose. All parts are rated for 15,000 psi (103.425 Mpa) and above.

5. Mercury Manometer

A mercury manometer was used to control the low back pressure on the consolidometer. It also served as down-stream flow indicator. Whenever the position of the mercury level changed the flow could be calculated.

B. Test Procedure:

The tests were to simulate the progressive burial of

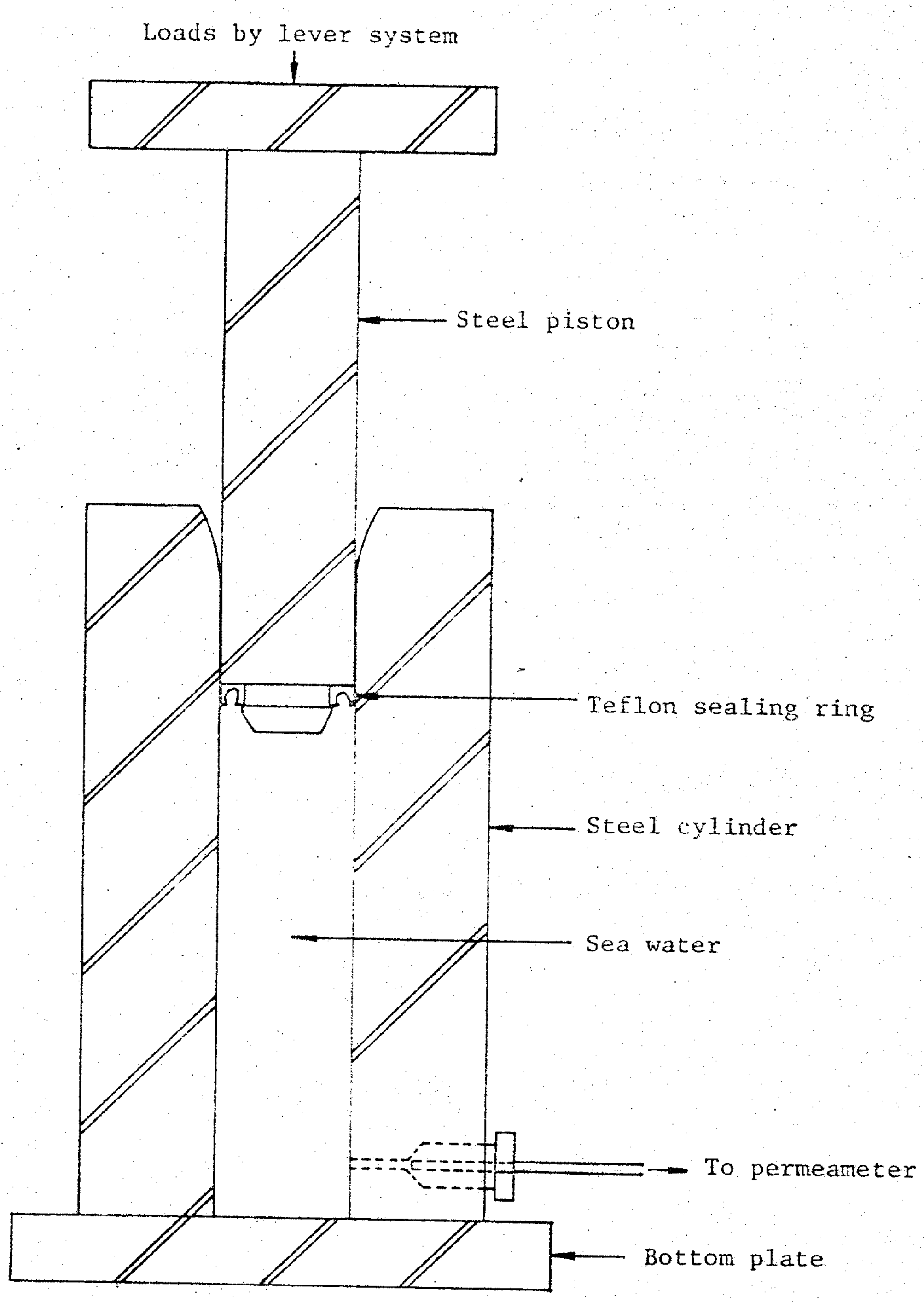


FIG. 8 .-Schematic Drawing of Water Pressure Source for the Permeability Test

marine sediments. The time span of real sedimentation takes millions of years. The laboratory tests took about two months to complete for each sample. The soil samples were taken from sea bottom at different locations. They were mixed with 3.5% reconstituted sea water and placed in a moisture room with 100% relative humidity for at least 72 hours to assure a uniform moisture content. The moisture content of the prepared soil samples was 130% to 160% in order to obtain the porosities of about 75% to 80%. The porosities of marine sediments at sea bottom is very high. Later this maximum porosity for each sediment was measured.

The test was started with the soil sample of about 2 inches high. After the load was applied to the soil sample the height was recorded and plotted with respect to the log time. When the curve flattened out the consolidation was assumed to be complete. The change of porosity was calculated as follows:

$$\Delta e = \frac{\Delta h(1+e_o)}{h} \quad \text{and} \quad n = \frac{e}{1+e}$$

where Δe = change of void ratio

Δh = change of sample height

e_o = original void ratio

h = original sample height before new load was applied

n = porosity before each new load was applied

After each increment of consolidation test, the permeability test was performed. The vertical consolidation load was kept constant while sea water was forced through the soil sample. The pressure at the downstream side of the consolidometer was kept constant by a mercury manometer. The pressure gradient and the amount of sea water that flowed through the soil sample was calculated from the manometer readings. The flow of sea water was plotted against time until a steady state was obtained. The flow and pressure gradient was used to calculate the coefficient of permeability using Darcy's law.

A detailed test procedure is given in Appendix

C. Calculation of Permeability

Darcy's equation is q = kia. The rate of flow, q, was calculated as described above after a steady state was reached. The pressure gradient, i, is the difference between head pressure and back pressure divided by the sample length. The cross sectional area of the soil sample is, a, and the same as the area of the consolidometer.

For convenience, the conversion of units was reduced to a constant number:

$$q = kia$$

or $$k = \frac{q}{ia}$$

$$q = \frac{(1/16)^2(\pi/4)(2.54)^2(\Delta h)}{(\Delta t)(60)} \text{ cm}^3/\text{sec}$$

$$i = \frac{(P-H/5.19)(70.43)}{(L)(2.54)} \text{ cm/cm}$$

$$a = (2.5)^2(\pi/4)(2.54)^2 = 31.67 \text{ cm}^2$$

$$k = \frac{\dfrac{(1/16)^2(\pi/4)(2.54)^2(\Delta h)}{(\Delta t)(60)}}{\dfrac{(P-H/5.19)(70.43)}{(L)(2.54)}(31.67)}$$

after reduction:

$$k = 3.76\text{x}10^{-7} \frac{(\Delta h)(L)}{(P-H/5.19)(\Delta t)} \text{ cm/sec}$$

where Δh = change of water level at downstream end, cm.

L = length of sample, in.

P = head water pressure, psi.

H = mercury height (back pressure), cm.

Δt = elapsed time, min.

CHAPTER IV

PRESENTATION AND DISCUSSION OF RESULTS

A. Description of Soil Samples

The soil samples for this study were taken from sea bottom at three different locations. The locations of the core samples are described in Table 3.

TABLE 3.-Locations of Three Soil Samples

Material	Location	Depth
Virginia sediment	Lat. 36 59' N Long. 76 07' W Chesapeake Bay	Surface of sea bottom in very shallow water
Mississippi Delta sediment	Lat. 29 28' N Long. 92 21' W Central Gulf of Mexico	20 meters below sea surface 0.5 meter below sea bottom
Gulf of Mexico sediment	Lat. 26 58' N Long. 94 15' W Western Gulf of Mexico	2,379 meters below sea surface 1.5 meters below sea bottom

The Atterberg limits, Unified Soil Classification, and specific gravity for each soil is given in Table 4.

The mineralogical analysis, determined by X-ray diffraction, of the three materials is given in Table 5.

TABLE 4.-Atterberg Limits, Classifications, and Specific Gravities of Three Soil Samples

Material	Liquid limit	Plastic limit	Plasticity index	Classification	Specific gravity
Virginia sediment	59.3	39.3	20	MH	2.70
Mississippi Delta sediment	113.2	32.8	80.4	CH	2.81
Gulf of Mexico sediment	91.0	34.0	57.0	CH	2.77

TABLE 5.-Mineralogical Analysis of Three Soil Samples

Clay Mineral	Virginia Sediment	Mississippi Delta Sediment	Gulf of Mexico Sediment
Smectite			
Mica	52.0		
Kaolinite	36.0		
Illite			
Vermiculite	7.0		
Quartz	5.0		

B. Consolidation Test Curves

The plot of sample height versus log of time for each increment of load and for each soil is given in the Appendix I. From the total change of sample height, the change in void ratio and change in porosity was computed. The e-log p curves of the three samples are shown in Fig. 10 The consolidation pressure for these tests ranged from 36 psi (248.2 KPa) to 10,125 psi (69.812 MPa). The test results are shown in Appendix I. The porosities were plotted on a log-log scale against consolidation pressures which showed the porosity as a function of vertical pressure in the process of progressive burial.

The power law equation was used as a mathematical model to fit the test data. It shows the model fits the curve very well within the range of test loads. The test data and model curves are shown in Figs. 11, 12, and 13. The power law equation was developed as follows:

$$\sigma = Gn^R, \quad R < 0 \text{ and } G > 0$$

where: σ = consolidation pressure, in psi

G = the intercept of the line when the decimal porosity is one

R = the slope of the line

n = decimal porosity

G and R are constants but peculiar for each type of soil.

A statistical analysis was done to obtain the best

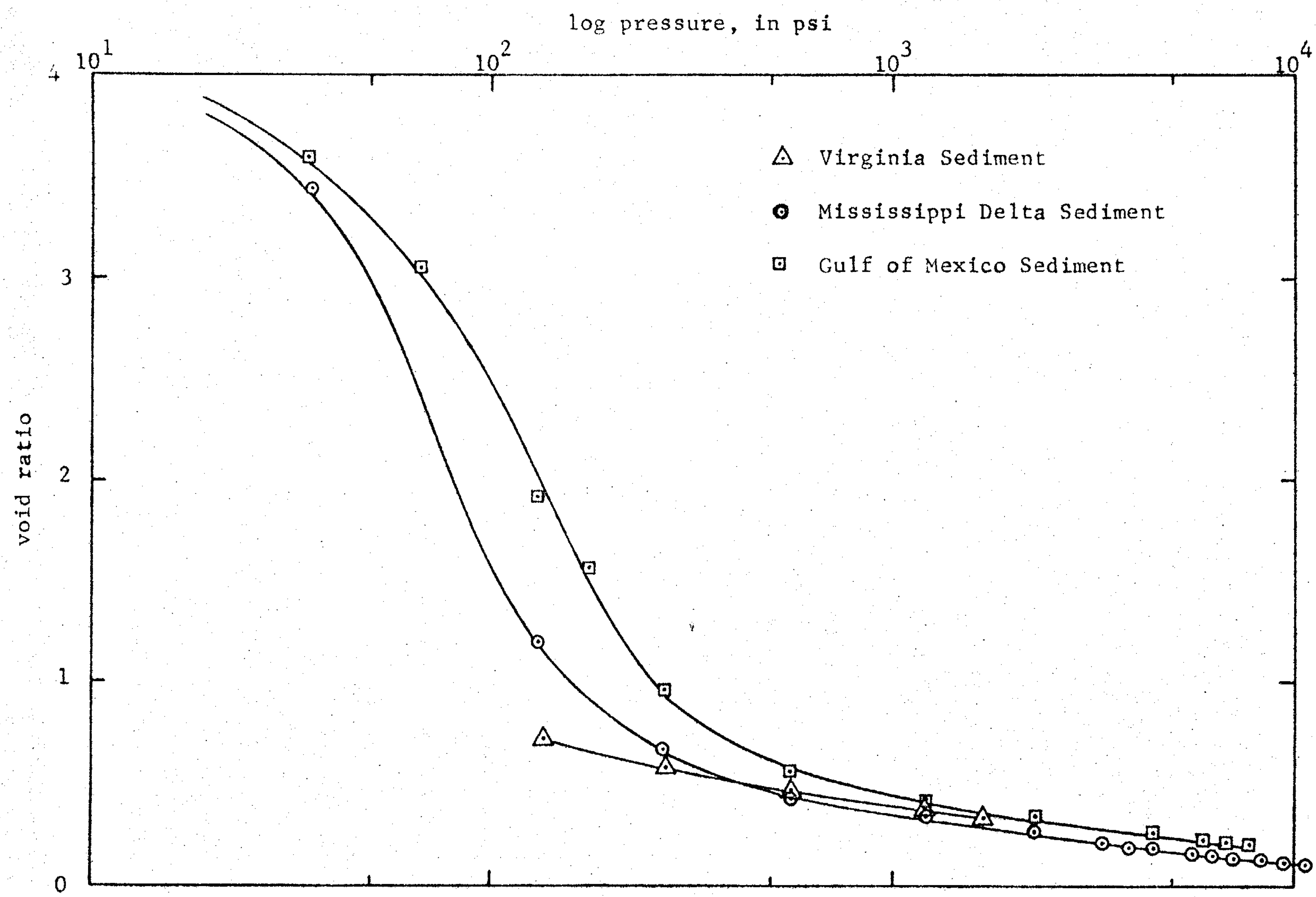


FIG. 10.-Relationship between Void Ratio and Log of Pressure for Three Soil Samples

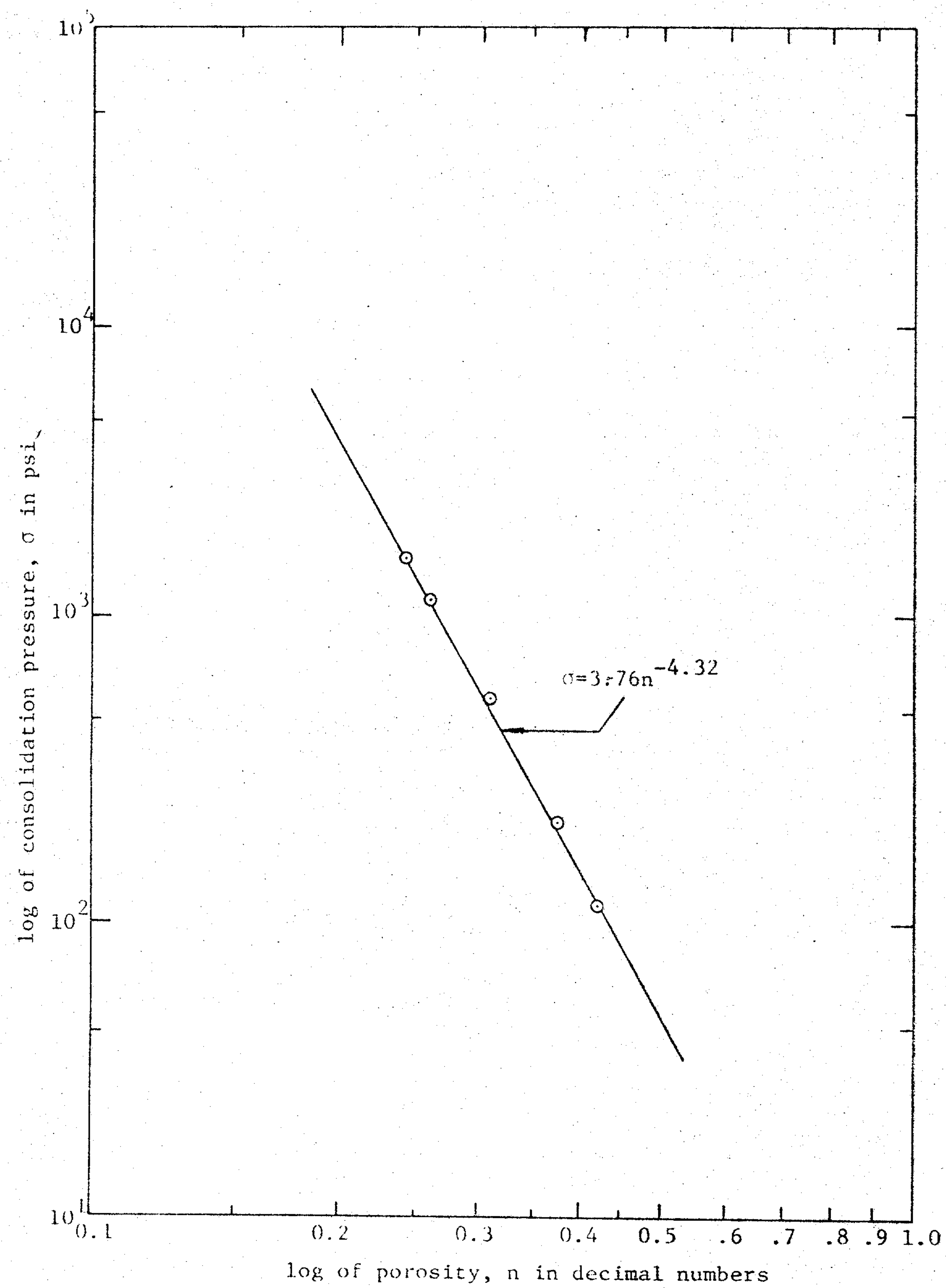


FIG. 11.-Relationship Between Consolidation Pressure and Porosity for Virginia Sediment by the Power Law Model

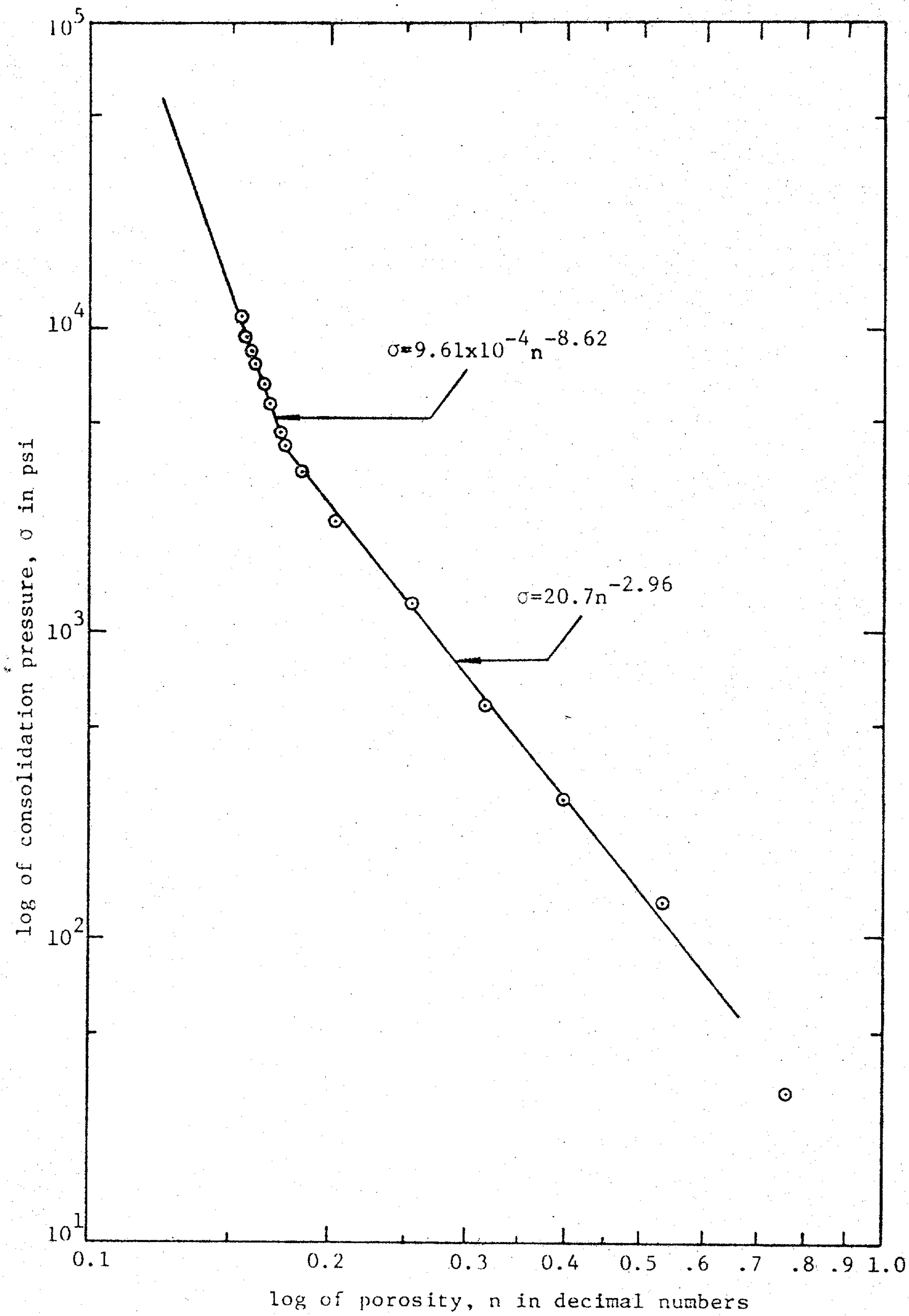


FIG. 12 .-Relationship Between Consolidation Pressure and Porosity for Mississippi Delta Sediment by the Power Law Model

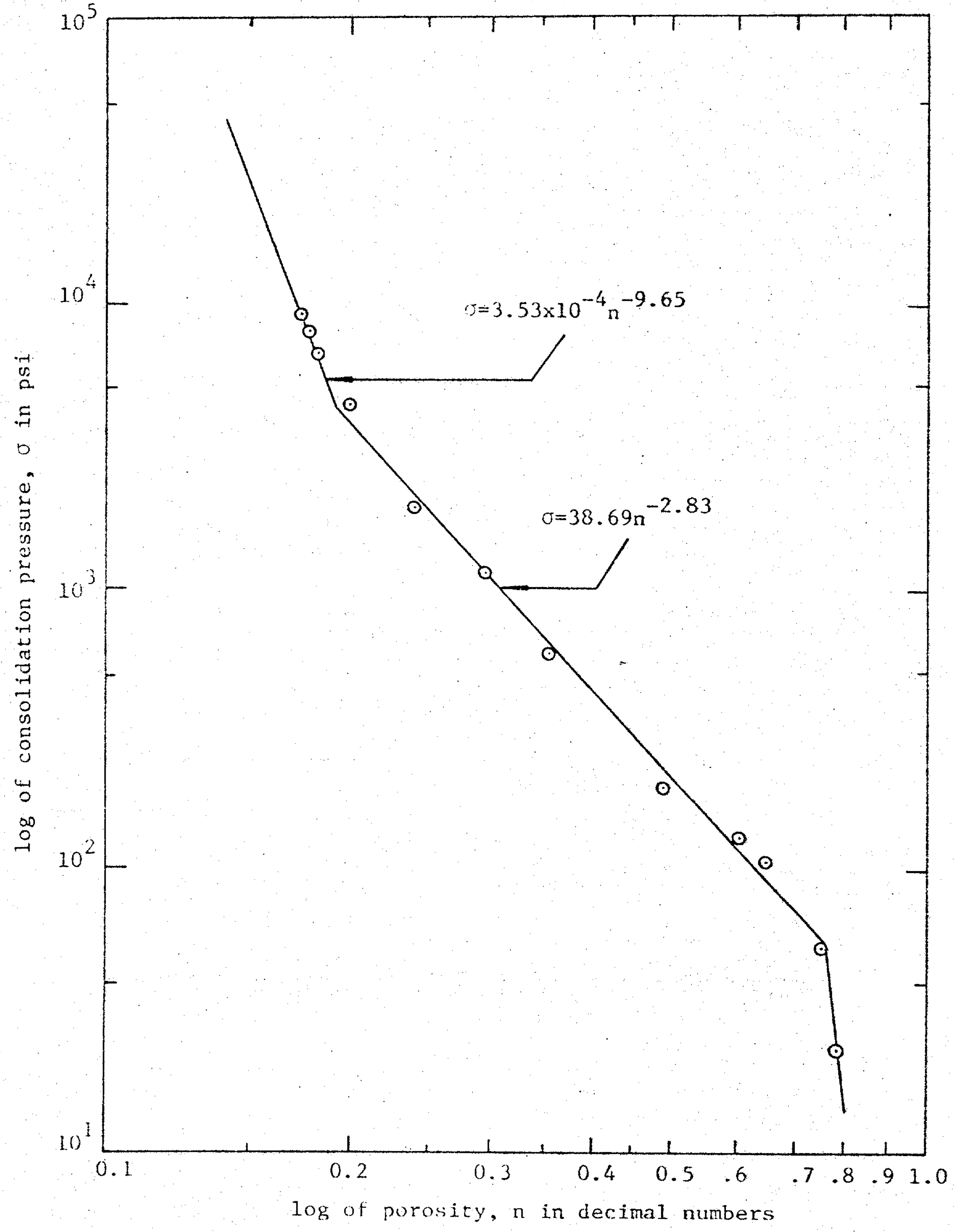


FIG. 13.-Relationship Between Consolidation Pressure and porosity for Gulf of Mexico Sediment by Power Law Model

correlation curve for the test data. The correlation index shows this power law model fits the data perfectly. The equations, thier ranges, and the correlation index for the three samples are given in Table 6.

Although the power law model fits the test data successfully, it is limited within a certain range of the porosity. The porosity of the marine sediments at mud line is very high but will not exceed a maximum value. This maximum porosity can be estimated by a sedimentation test. The detailed test procedure is stated in Appendix III. The results show that the maximum porosity for Virginia sediment is 84.3%, for Mississippi Delta sediment is 92.3%, and for Gulf of Mexico sediment is 92.0%. The curve of the relationship between consolidation pressure and porosity then has to approach these maximum values for an infinitely small value of pressure. Also for the other end of the curve, it has to approach a minimum value of porosity when the pressure is infinitely large. The curve then seems to be asymptotic to a minimum number and a maximum number at both ends.

Another mathematical model, Fermi function, was used to fit the data with more realistic value. The equation was developed as follows:

$$\log n = \frac{-1}{1 + e^{A\log\sigma + B}}$$

TABLE 6.-Equations for Consolidation Pressure-Porosity Relationships for Three Samples by Using the Power Law Model

Material	Equation	Range	Correlation
Virginia sediment	$\sigma = 3.76n^{-4.32}$	$143 \leqslant \sigma \leqslant 1716$ psi	$r^2 = 0.991$
Mississippi Delta sediment	$\sigma = 20.74n^{-2.96}$	$36 \leqslant \sigma \leqslant 4004$ psi	$r^2 = 0.99$
	$\sigma = 9.61 \times 10^{-4} n^{-8.62}$	$4004 \leqslant \sigma \leqslant 10125$ psi	$r^2 = 0.96$
Gulf of Mexico sediment	$\sigma = 38.69n^{-2.83}$	$72 \leqslant \sigma \leqslant 4600$ psi	$r^2 = 0.99$
	$\sigma = 3.53 \times 10^{-4} n^{-9.65}$	$4600 \leqslant \sigma \leqslant 8318$ psi	$r^2 = 0.99$

or $$\log \sigma = \frac{1}{A}\left[\log_e\left(-\frac{1}{\log n} - 1\right) - B\right]$$

where σ = consolidation pressure, in psi

n = decimal porosity

e = 2.71828

A = the slope of the function at the point of reflection

B/A = the distance from the point of reflection to Y axis in the rectangular co-ordinate system

The Fermi functions derived for Mississippi Delta sediment and Gulf of Mexico sediment are shown in Figs 14. and 15. Table 7 shows the equations of the relationship between consolidation pressure and porosity by the Fermi function model.

C. Permeability Test Curves

The permeability tests were performed after each increment of consolidation test. The flow was plotted against time until a steady state of flow was achieved. It was assumed achieving a steady state when the flow stayed constant with increasing in time. The plot of flow versus time is given in Appendix I. The calculation of permeability is stated in Chapter III. The results of permeability tests are given in Appendix I.

The permeabilities were plotted against porosities on a log-log scale. The power law model was used to fit the test data. The curves are shown in Figs 16, 17, and 18.

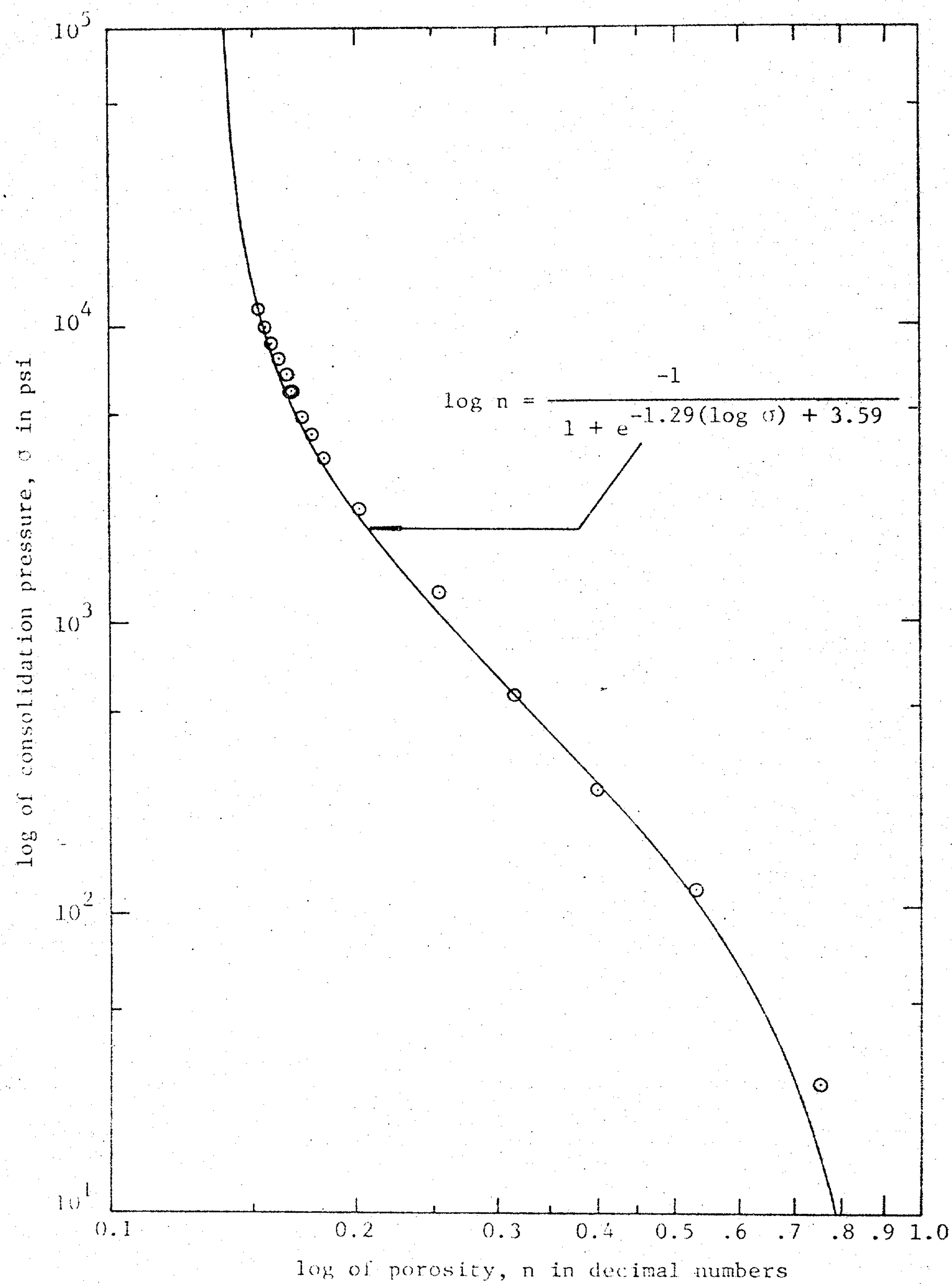


FIG. 14.-Relationship Between Consolidation Pressure and Porosity for Mississippi Delta Sediment by Fermi Function Model

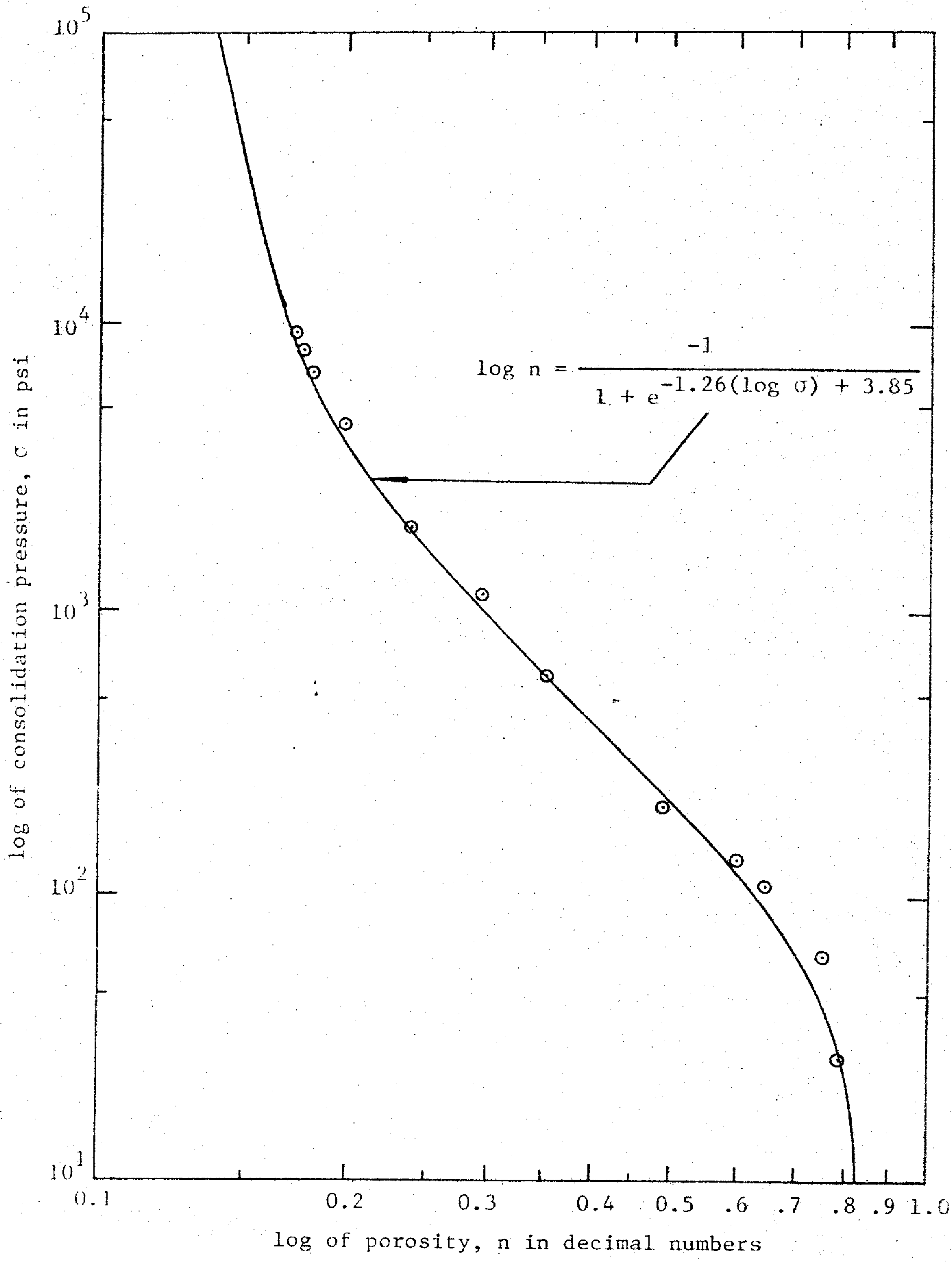


FIG. 15.-Relationship Between Consolidation Pressure and Porosity for Gulf of Mexico Sediment by Fermi Function Model

TABLE 7.-Equations for Consolidation Pressure-Porosity Relationships for Two Soil Samples by Using the Fermi Function Model

Material	Equation	Range	Correlation
Mississippi Delta sedimeny	$\log n = \frac{-1}{1+e^{-1.29\log\sigma+3.59}}$ or $\log \sigma = \frac{-1}{1.29}\left[\log_e(-\frac{1}{\log n}-1)-3.59\right]$	$0.1 \leqslant n \leqslant 1.0$	$r^2 = 0.981$
Gulf of Mexico sediment	$\log n = \frac{-1}{1+e^{-1.26\log\sigma+3.85}}$ or $\log \sigma = \frac{-1}{1.26}\left[\log_e(-\frac{1}{\log n}-1)-3.85\right]$	$0.1 \leqslant n \leqslant 1.0$	$r^2 = 0.965$

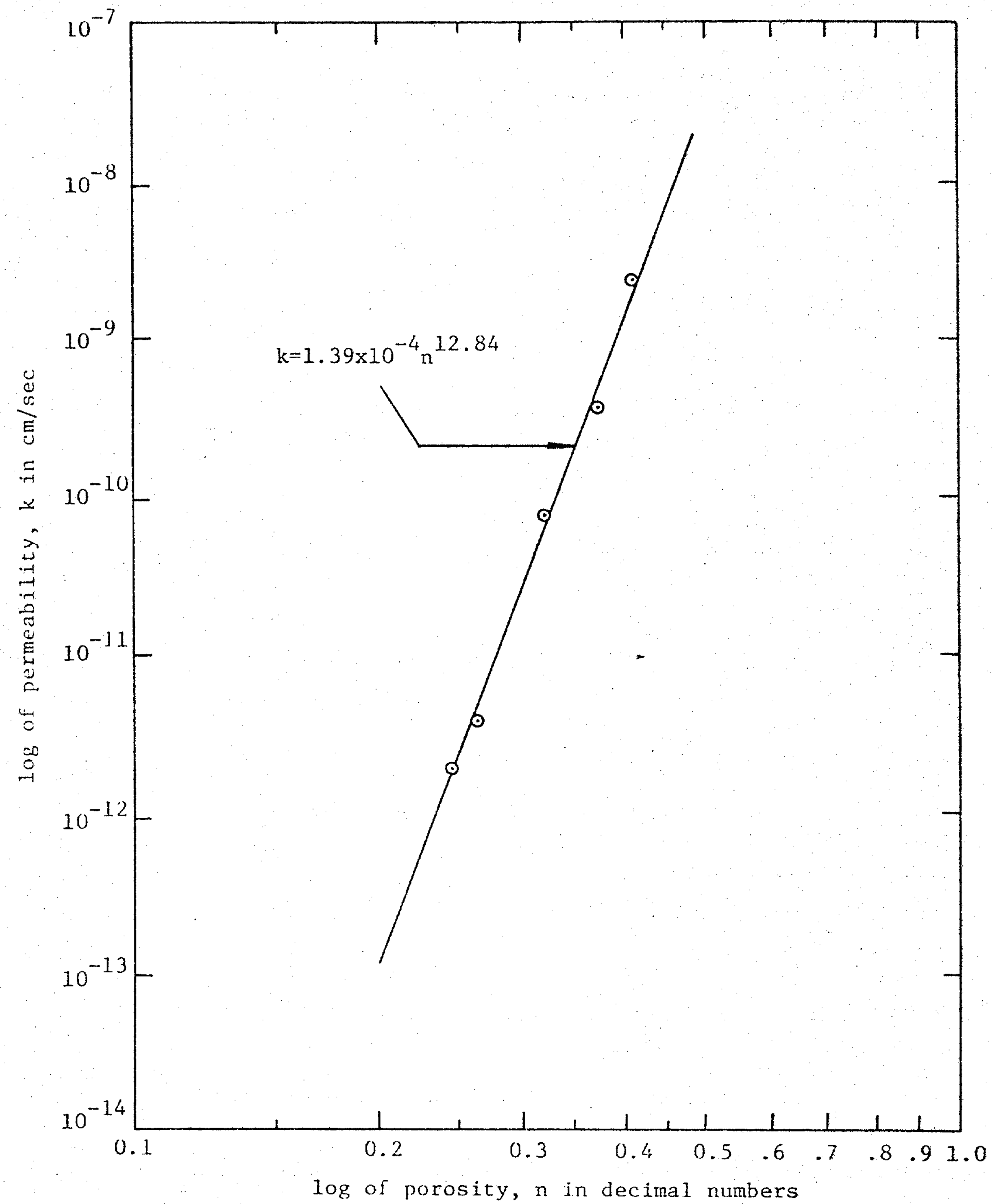


FIG. 16.-Relationship Betwwen Permeability and Porosity for Virginia Sediment by Power Law Model

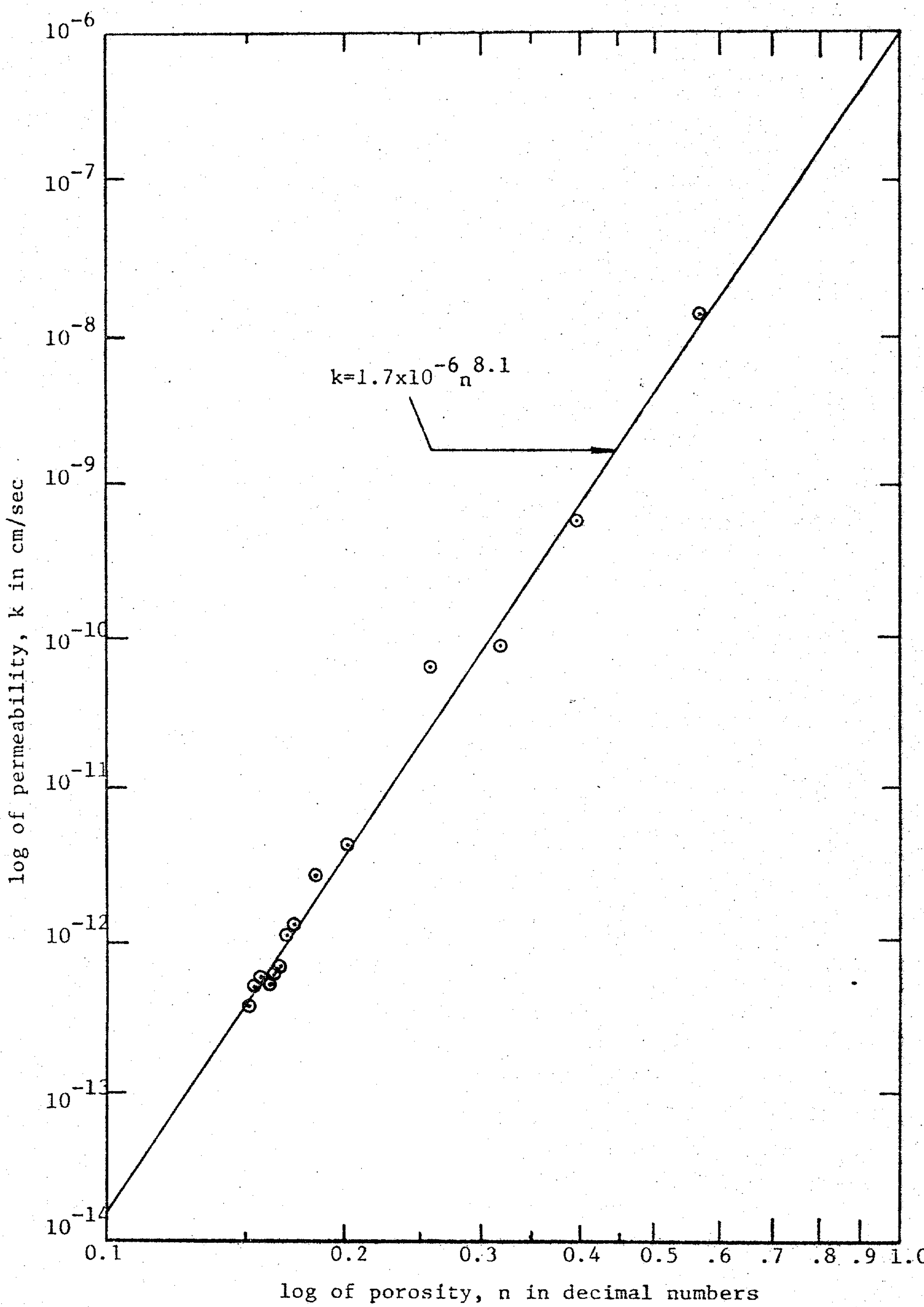


FIG. 17.-Relationship Between Permeability and Porosity for Mississippi Delta Sediment by Power Law Model

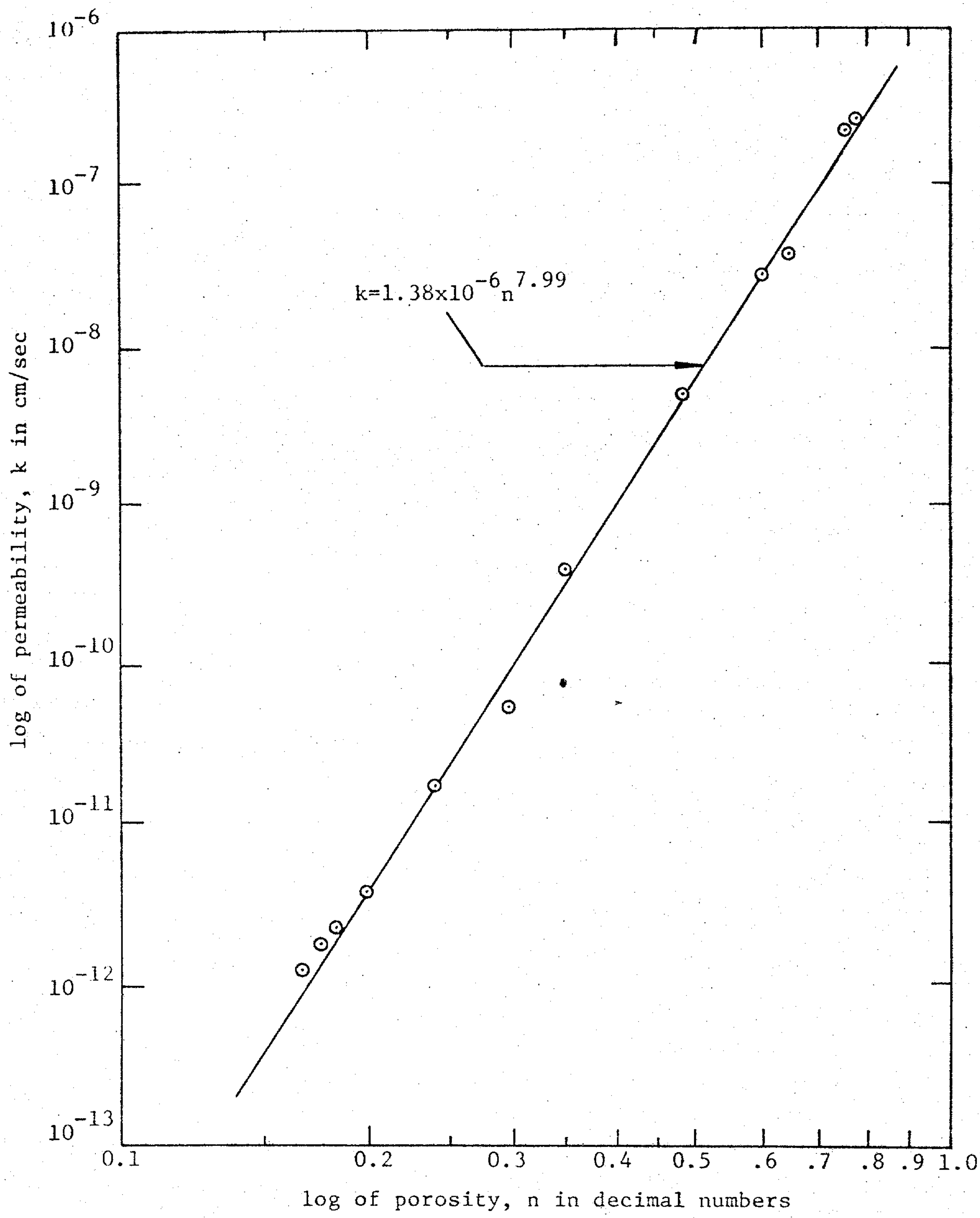


FIG. 18.-Relationship Between Permeability and Porosity for Gulf of Mexico Sediment by Power Law Model

The equations derived for each sample are given in Table 8. The straight line relationship on the log-log scale fits the test data of permeability and porosity very well. However, for the porosity greater or smaller than the test range the relationship is unknown.

TABLE 8 .-Relationships between Permeability and Porosity for Three Soil Samples by Using the Power Law Model

Material	Equation	Range	Correlation
Virginia sediment	$k = 1.39 \times 10^{-4} n^{12.84}$	$24\% \leqslant n \leqslant 41.9\%$	$r^2 = 0.992$
Mississippi Delta sediment	$k = 1.71 \times 10^{-6} n^{8.1}$	$15.17\% \leqslant n \leqslant 54.93\%$	$r^2 = 0.986$
Gulf of Mexico sediment	$k = 1.38 \times 10^{-6} n^{7.99}$	$17.2\% \leqslant n \leqslant 78\%$	$r^2 = 0.991$

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A new experimental method of obtaining high pressure consolidation test data and direct measurement of permeability has been developed. The high powered lever mechanism does provide a valid method of performing high pressure consolidation and permeability tests. Based on the results obtained it is concluded that:

1. The marine sediments tested did not exhibit the usually assumed linear relationship between void ratio and log of consolidation pressure.
2. There is maximum porosity for each marine sediment.
3. Permeabilities of clays can be measured directly and there is no need to estimate this value using the Terzaghi's consolidation theory. In fact, there can be wide discrepancies between the measured permeability and that permeability computed from a consolidation test.
4. The Fermi function seems to be a good model for the relationship between the porosity and the consolidation pressure.
5. The power law seems to be an excellent model for the relationship between porosity and permeability.
6. The permeability decreased at least seven orders of magnitude faster than the porosity for the materials tested.

Further work should be done to include a controlled thermal environment as a method to investigate the temperature effect on the relationship between pressure, permeability, and porosity. A pore water pressure measuring device on the consolidometer would provide more information on calculating the effective pressure when the soil sample is under consolidation. More soil samples should be tested to provide a general correlation among the same type of soil.

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APPENDIX I

BASIC CURVES AND RESULTS OF CONSOLIDATION AND PERMEABILITY TESTS

TABLE 9 .--Results of Consolidation and Permeability Test for Virginia Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	1.4248	2.533	71.7	-
143	0.6938	0.721	41.9	2.3×10^{-9}
286	0.6432	0.595	37.3	3.3×10^{-10}
572	0.5942	0.473	32.1	8.0×10^{-11}
1,144	0.5469	0.356	26.3	3.6×10^{-12}
1,716	0.5309	0.316	24.0	1.9×10^{-12}

TABLE 10.-Results of Consolidation and Permeability Test for Mississippi Delta Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	1.4459	3.710	78.77	-
36	1.3569	3.420	77.38	-
143	0.7128	1.220	54.93	1.5×10^{-8}
286	0.5061	0.650	39.34	5.8×10^{-10}
572	0.4467	0.460	31.28	8.3×10^{-11}
1,144	0.4129	0.350	25.65	7.0×10^{-11}
2,288	0.3855	0.260	20.37	4.3×10^{-12}
3,432	0.3747	0.220	18.07	2.6×10^{-12}
2,288	0.3755	0.223	18.25	-
4,004	0.3707	0.210	17.17	1.2×10^{-12}
4,576	0.3685	0.200	16.69	1.1×10^{-12}
5,720	0.3669	0.195	16.33	4.9×10^{-13}
6,570	0.3661	0.193	16.15	5.5×10^{-13}
7,714	0.3650	0.189	15.89	4.0×10^{-13}
8,500	0.3645	0.187	15.78	4.5×10^{-13}
9,313	0.3633	0.183	15.50	4.0×10^{-13}
10,125	0.3619	0.179	15.17	3.8×10^{-13}

TABLE 11-Results of Consolidation and Permeability Test for Gulf of Mexico Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	2.1255	3.66	78.5	-
36	2.0716	3.54	78.0	2.8×10^{-7}
72	1.8327	3.01	75.1	2.4×10^{-7}
143	1.3131	1.88	65.2	4.0×10^{-8}
179	1.1568	1.53	60.5	3.1×10^{-8}
286	0.8852	0.94	48.5	1.2×10^{-9}
572	0.7026	0.54	35.1	3.0×10^{-10}
1,144	0.6467	0.42	29.4	6.4×10^{-11}
2,288	0.5991	0.31	23.8	1.3×10^{-11}
4,576	0.5701	0.25	19.9	3.2×10^{-12}
6,292	0.5541	0.215	17.7	1.9×10^{-12}
7,170	0.5529	0.212	17.5	1.6×10^{-12}
8,318	0.5509	0.208	17.2	1.2×10^{-12}

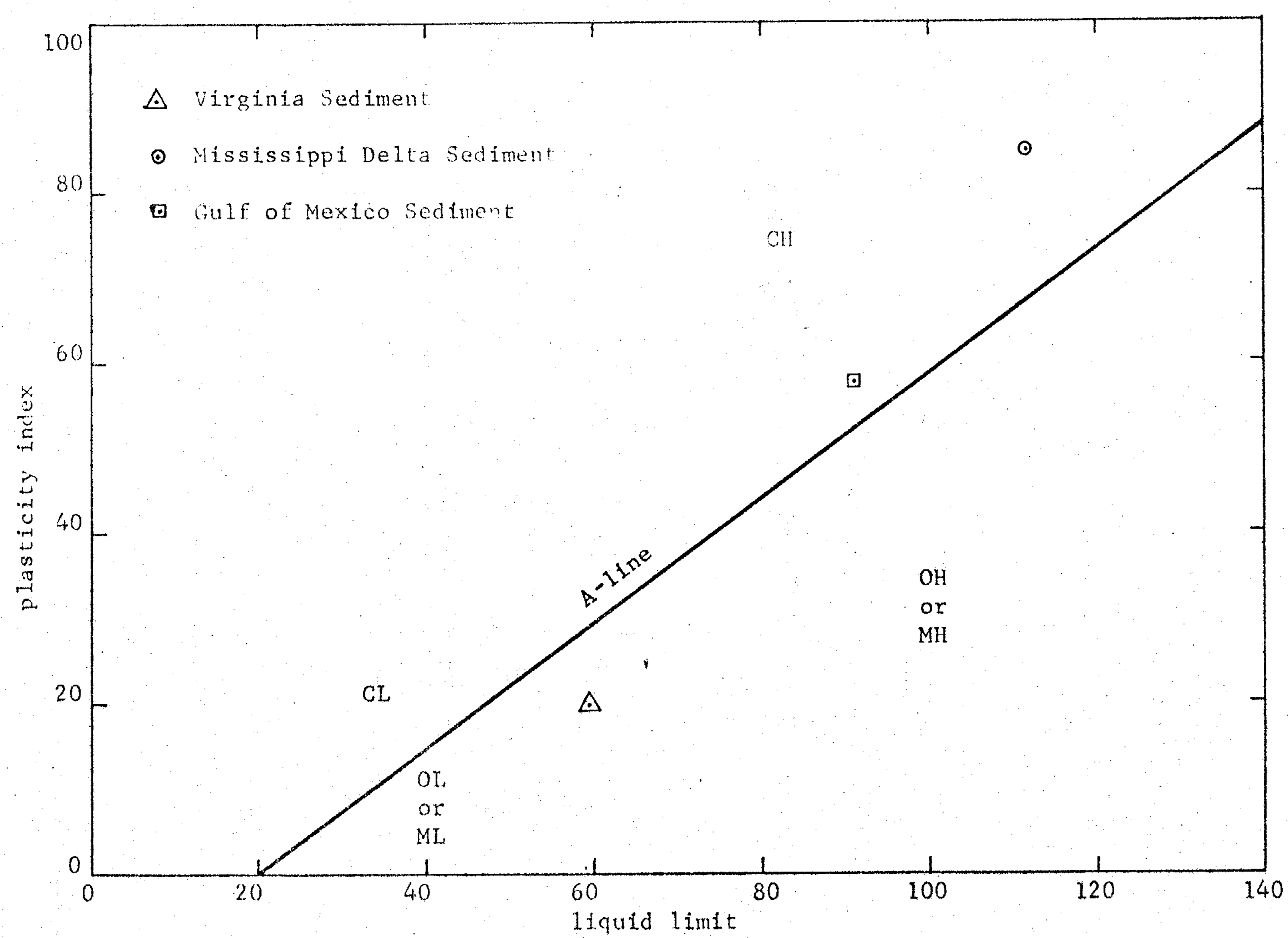

FIG. 19.-Plasticity Chart for Laboratory Classification of Fine-Grained Soils

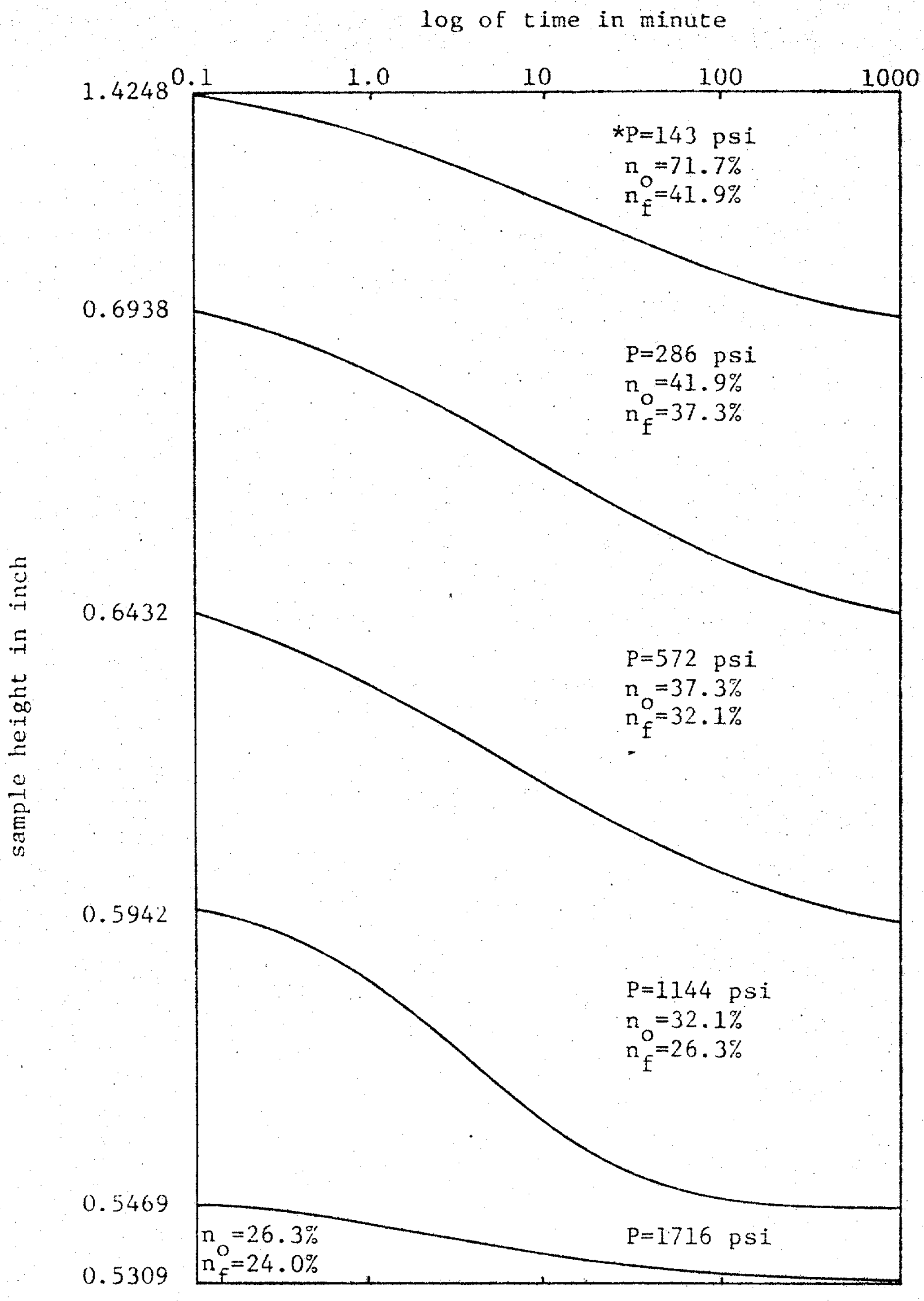

FIG. 20.-Relationship Between Sample Height and Log of Time of Consolidation Test for Virginia Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

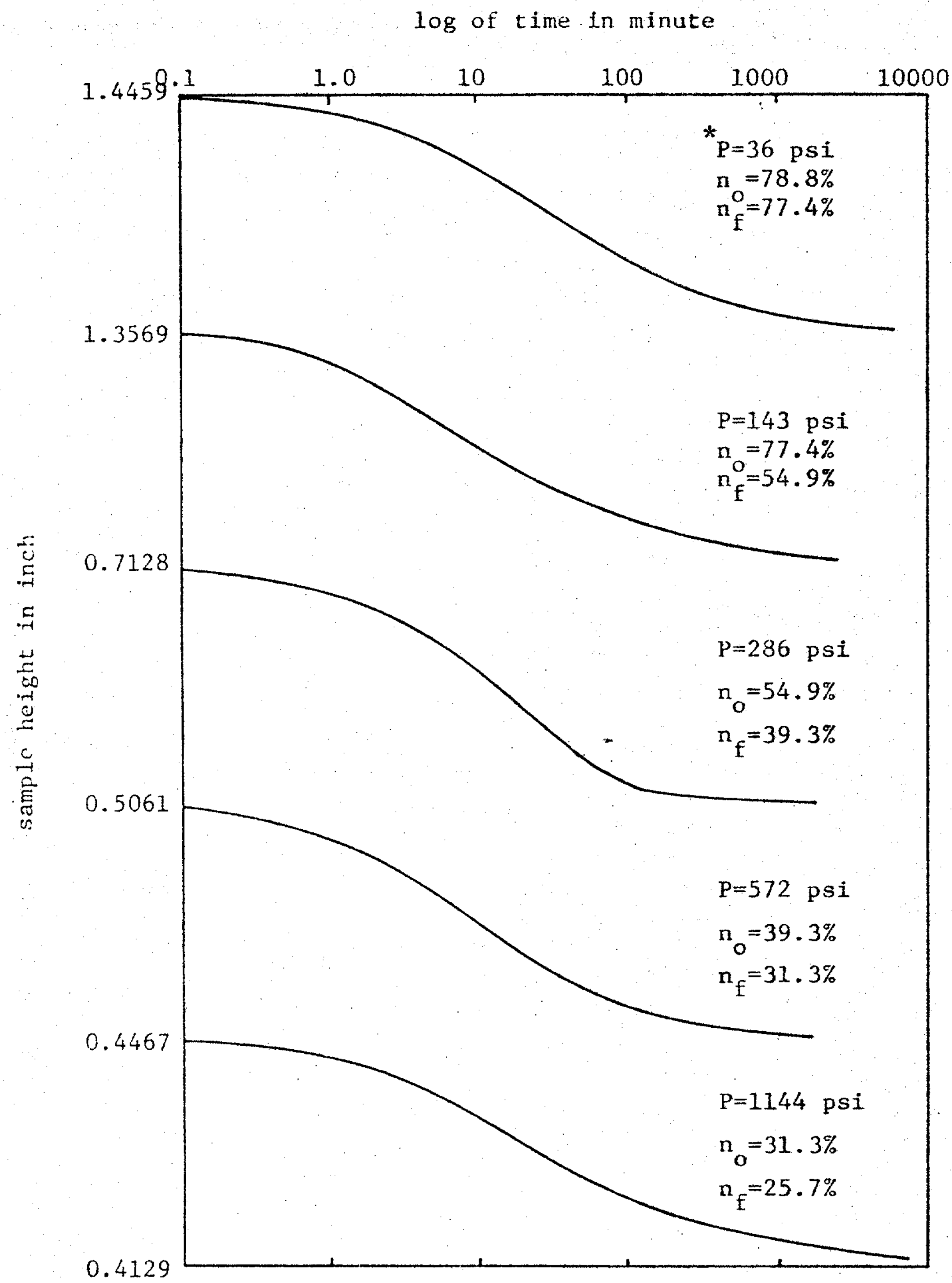

FIG. 21 .-Relationship Between Sample Height and Log of Time of Consolidation Test for Mississippi Delta Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

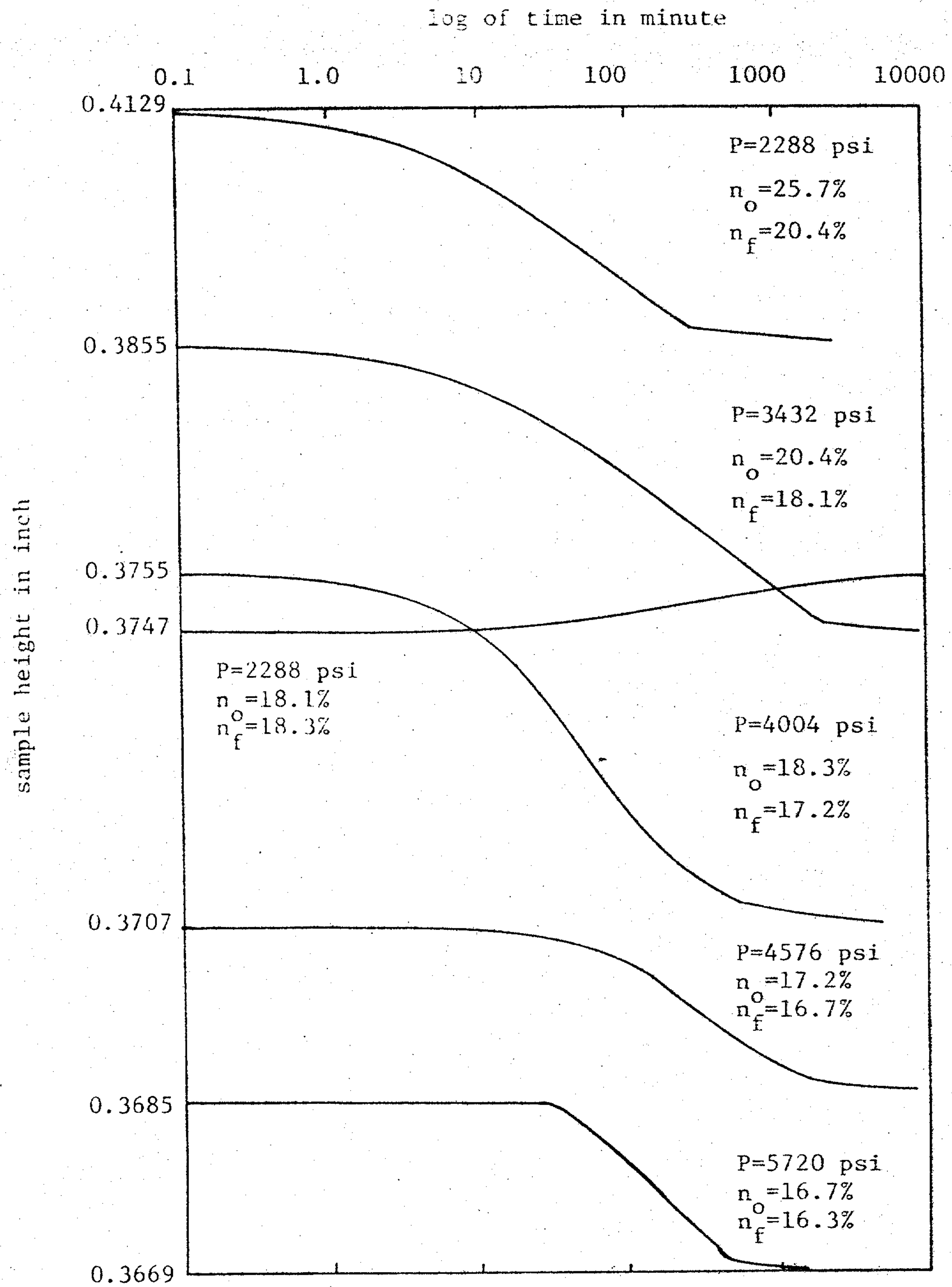

FIG. 21 . (continued)

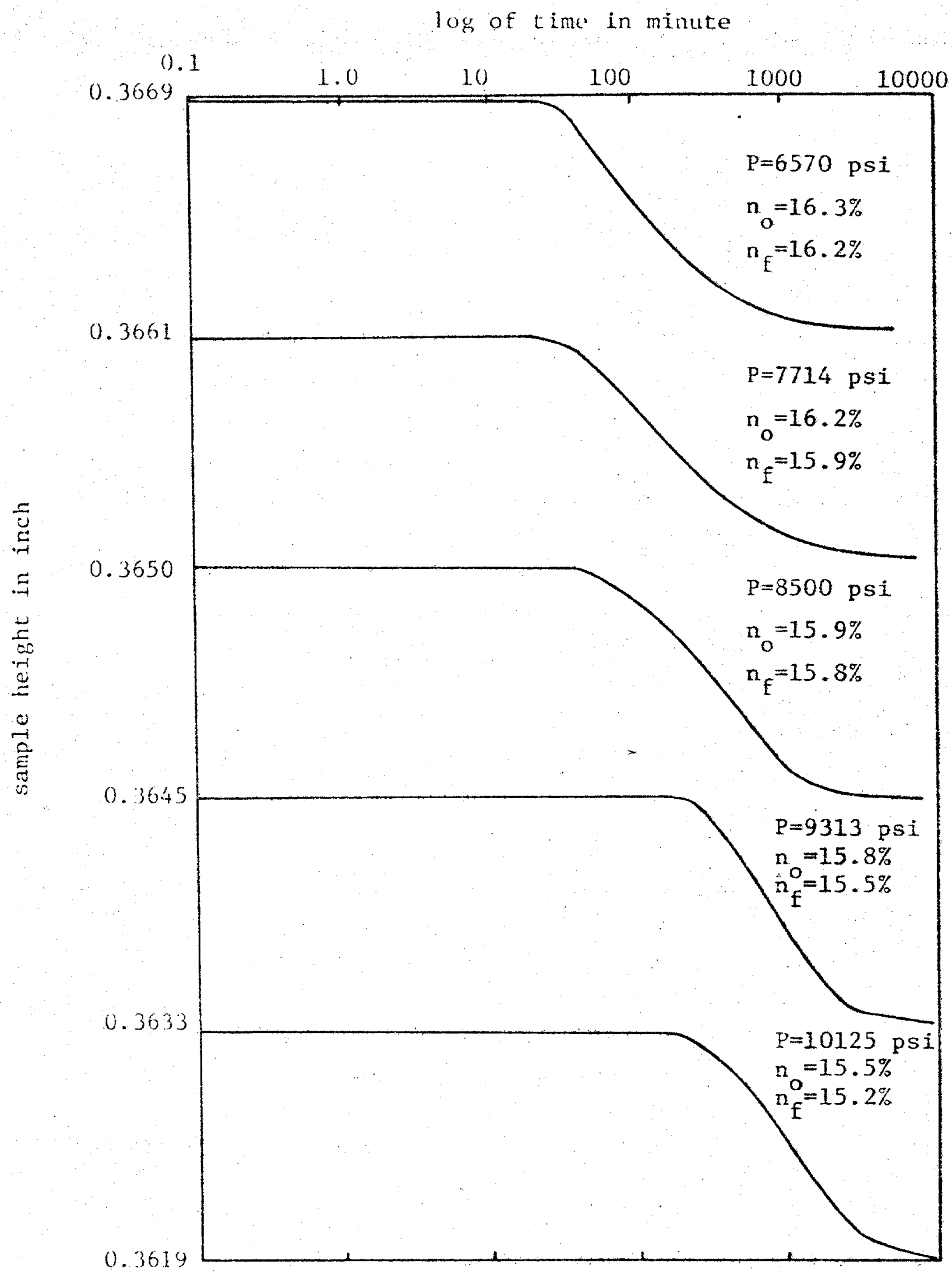

FIG. 21. (continued)

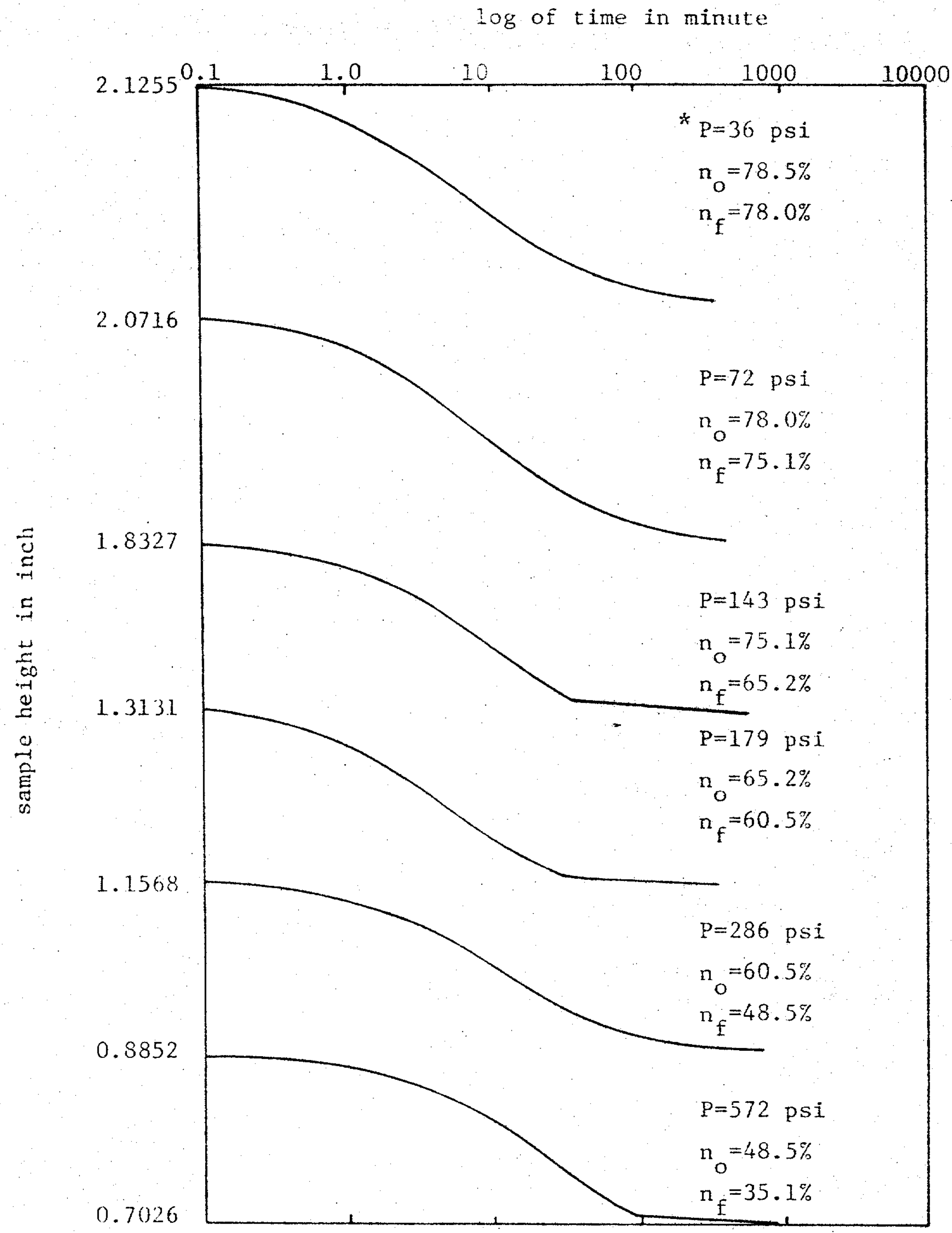

FIG. 22.-Relationship Between Sample Height and Log of Time of Consolidation Test for Gulf of Mexico Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

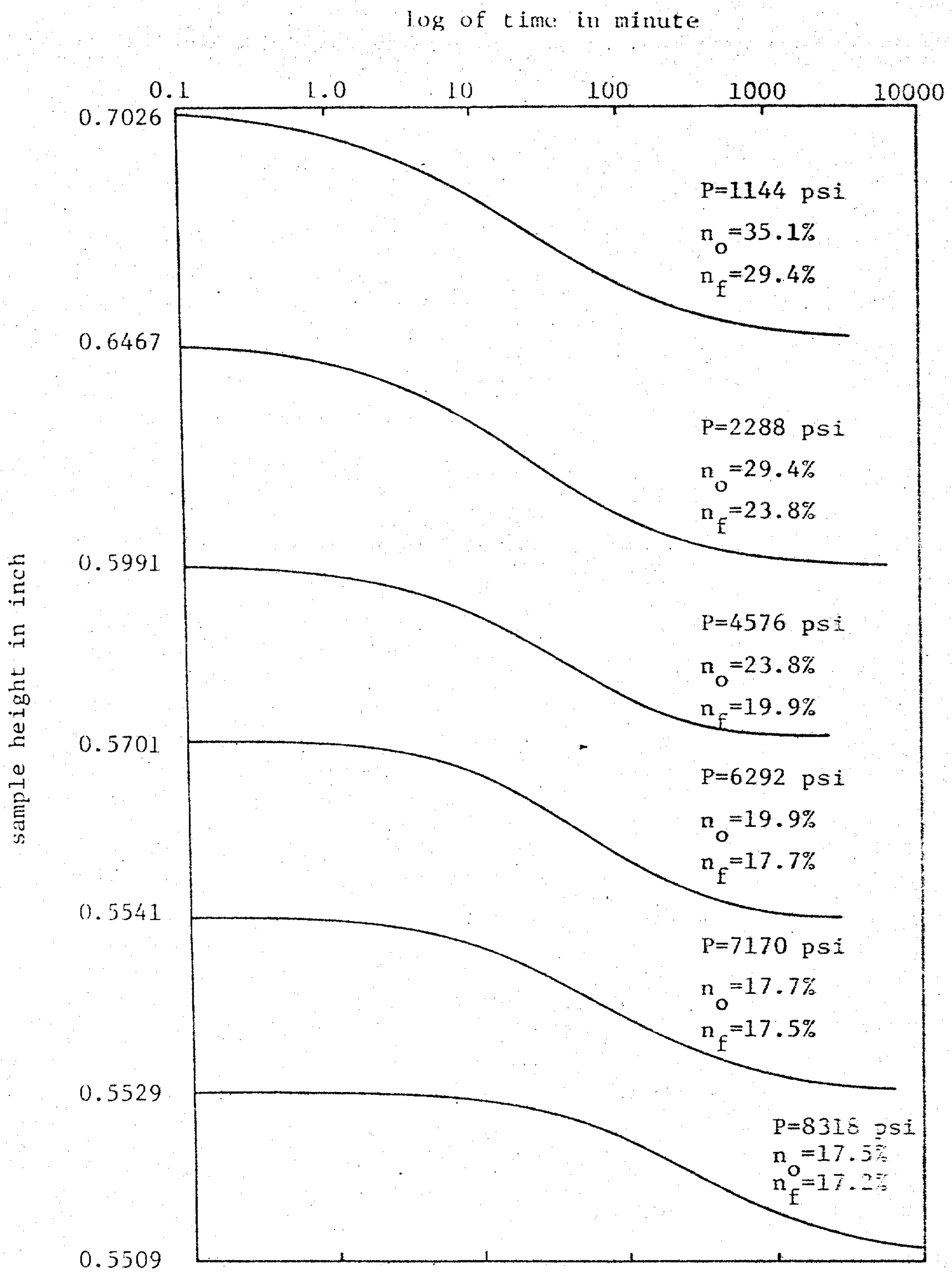

FIG. 22. (continued)

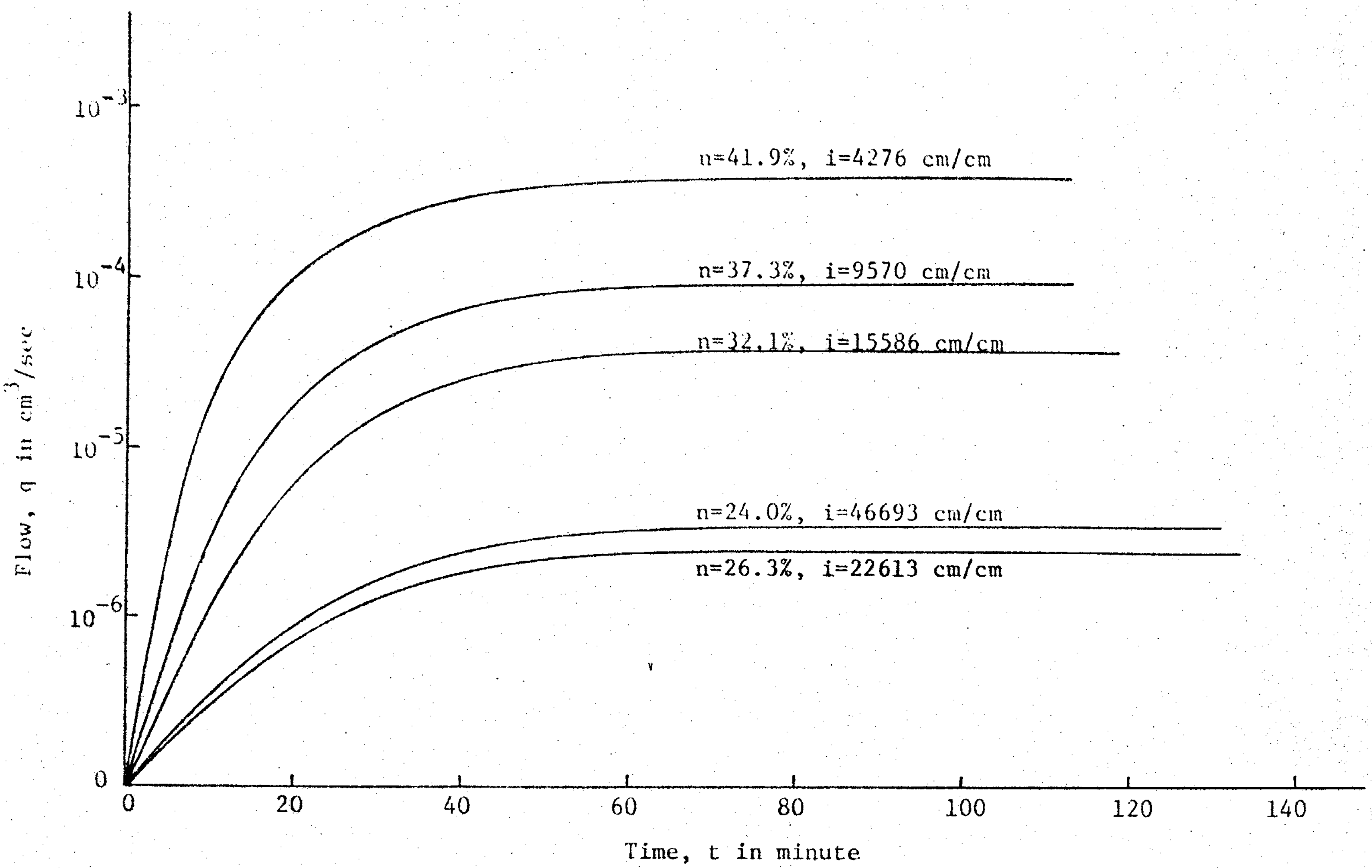

FIG. 23.-Relationship Between Flow and Time of Permeability Test for Virginia Sediment

APPENDIX II

TEST PROCEDURES FOR CONSOLIDATION AND PERMEABILITY TEST

1. Mix the soil sample with sea water of 3.5% salinity completely, blend the soil if necessary. The moisture content of the soil has to be about 150%. Put the soil in a ziploc plastic bag and place in a moisture room with 100% relative humidity for at least 72 hours.
2. Boil the porous stones for at least 30 minutes to remove entrapped air.
3. Put the bottom piston and spacers in the consolidometer to a desired height. Connect the tubing from the bottom piston to the manometer. Saturate the connecting lines with sea water. Put the porous stone on the top of the piston. Fill sea water to the surface of the porous stone. Put a filter paper on the porous stone. Measure the height to the top of filter paper.
4. Put the soil sample into the consolidometer carefully and place the filter paper and porous stone on top of the soil. Use the spare soil to measure the moisture content. Measure the height to the top of the porous stone. The filter papers were used to prevent fine particles from washing into the porous stones.
5. Put the loading piston on the porous stone and set the consolidometer in the loading position.
6. Set the dial gauge on the loading piston.

7. Record dial gauge reading and water level on both ends of the soil sample.
8. Apply the load on the hanger and record the dial reading at time intervals of 0, 1/4, 1/2, 1, 2, 4, 8, 15, 30, 60 minutes and 2, 4, 8, ··· hours. Plot the dial reading vs log time until secondary consolidation is obtained.
9. Calculate change of volume, void ratio, porosity, and moisture content.

$$\Delta e = \frac{\Delta h(1+e)}{h}, \quad n = \frac{e}{1+e}$$

where Δe = change of void ratio

Δh = change of sample height

e = original void ratio

h = original sample height

n = porosity

10. Set the piston-cylinder permeameter in loading position.
11. Apply water pressure on the soil sample by putting the load on the piston of permeameter.
12. Record the change of water level and mercury level in manometer at the downstream end with respect to time.
13. Repeat steps 6 - 12 for the next load increment.
14. The calculation of permeability is stated in page

APPENDIX III

TEST PROCEDURE FOR ESTIMATING MAXIMUM POROSITY OF MARINE SEDIMENT AT MUD LINE

1. Clean the 100 c.c. graduate throughly and weigh it.
2. Put the soil in the graduate for about 10 g in wet weight.
3. Add sea water in the graduate to about 80 c.c. mark.
4. Shake the graduate thoroughly for about five minutes.
5. Put the graduate on the table and let the soil to settle.
6. Record the level of the soil surface.
7. Plot the settlement, height of the soil, against time until the curve is flat.
8. Remove the excess water by suction to the surface of the soil.
9. Weigh the graduate with soil.
10. Oven dry and obtain the moisture content.
11. Calculate for the porosity of the soil. Total volume, moisture content, and specific gravity are known.
12. Figure   shows three testing graduate.

VITA

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